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AN ANALYSIS OF THE
ADVANTAGES AND DISADVANTAGES OF THE
AIR FORCE STANDARD CONTROL PANEL

THESIS
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Captain, USAF

AFIT/GEM/DEE/89S-15

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THESIS

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Kevin E. Rumsey

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List of Symbols

ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
CE	Civil Engineering
CERL	Construction Engineering Research Laboratory
CES	Civil Engineering Squadron
DDC	Direct Digital Control
E/P	Electronic to Pneumatic
EMCS	Energy Monitoring and Control System
ETL	Engineering Technical Letter
FSC	Fan Speed Control
HVAC	Heating, Ventilating and Air Conditioning
HW	Hot Water
IVD	Inlet Vane Damper
NRC	National Research Council
OA	Outside Air
PB	Proportional Band
PI	Proportional plus Integral
PID	Proportional plus Integral plus Derivative
PSI	Pounds per Square Inch
RA	Return Air
RTD	Resistance Temperature Detector
SA	Supply Air
SLDC	Single Loop Digital Control
Tn	Reset Time
TR	Throttling Range
VAV	Variable Air Volume

Abstract

This study conducted research into the field of heating, ventilating, and air conditioning (HVAC) controls. Specifically, the research attempted to determine if the Air Force Standard Control Panel would aid in solving the Air Force's problems with complicated and unreliable HVAC controls.

The researcher conducted an experiment and a Delphi survey of experts. The experiment compared the Standard Panel with a pneumatic built-up system. The analysis included a comparative investigation of the installation, calibration and operations of each system, and a statistical analysis and comparison of the drift of each system's mixed air and supply air controllers. The Delphi survey included eight experts in the controls field who were familiar with the Air Force Standard Panel. The survey included seven questions and was conducted in three rounds.

No conclusions could be drawn from the statistical results of the experiment. However, the researcher concluded from the results of the qualitative portion of the experiment and the consensus of the Delphi experts that the Standard Panel was not superior to other controls systems in terms of design and installability (to include calibration) but was superior in terms of ability to maintain setpoint (to include overall operability) and diagnostics capability.

This research is valuable to the Civil Engineering (CE) community, the Air Force, and the controls industry as a whole because it attempted to include all aspects of all controls systems. Additionally, it performed a head-to-head comparison of two control systems. If the conclusions reached by this research are applied, benefits to the Civil Engineers in terms of reliable and maintainable control systems, as well as to CE's customers in terms of a comfortable environment, will most certainly be realized.

AN ANALYSIS OF THE ADVANTAGES AND DISADVANTAGES OF THE AIR FORCE STANDARD CONTROL PANEL

I. Introduction

General Issue

The Air Force spends millions of dollars each year constructing and maintaining heating, ventilating, and air conditioning (HVAC) systems. An HVAC system consists of four subsystems: heating system, air distribution system, cooling system, and controls. The controls are the brain of the system that regulates the air flow and air temperature to ensure the building occupants have a comfortable environment in which to function. Maintaining a comfortable environment is not simple, however, and many of the control systems purchased are very complicated, too complicated for the technicians who must maintain them. Some control systems include computers which are not "user friendly" to the technicians. Many other control systems have components which go out of calibration within a few months. Technicians frustrated by problems like these frequently bypass the HVAC control systems. These problems occur not only in the Air Force, but in the controls industry as a whole (Haines, 1985a:146). This creates uncomfortable conditions for the building occupants and leads to excessive energy losses.

To eliminate these problems, the Air Force developed the Standard Control Panel. This Panel has a model format with easily-understandable gauges designed to enable the technician to quickly diagnose the status of the entire HVAC system (see Figures 1 and 2). Additionally, the Panels are constructed using industrial-grade components which should stay calibrated for longer periods of time (Hittle, 1986:243). The Panels are new, however, and have been mandatory only since July 1987 (Flora, 1987:1,2) so no research has been conducted to establish their superiority. They are also very expensive -- up to four times as expensive as the typical built-up, or separate component system which was common practice in the past.

Specific Problem

This research determined if the new Standard Control Panel would aid in solving the Air Force's problems with complicated and unreliable HVAC controls. This determination required a comparison involving four aspects of the new Standard Control Panel systems and other control systems. These four areas are ease and completeness of designing each system, ease of installation, reliability of the components, and the ease with which a technician can diagnose problems within the entire HVAC system through the controls. Based on the comparison results, the research further concluded if the Panels are worth the additional cost compared to other control systems.

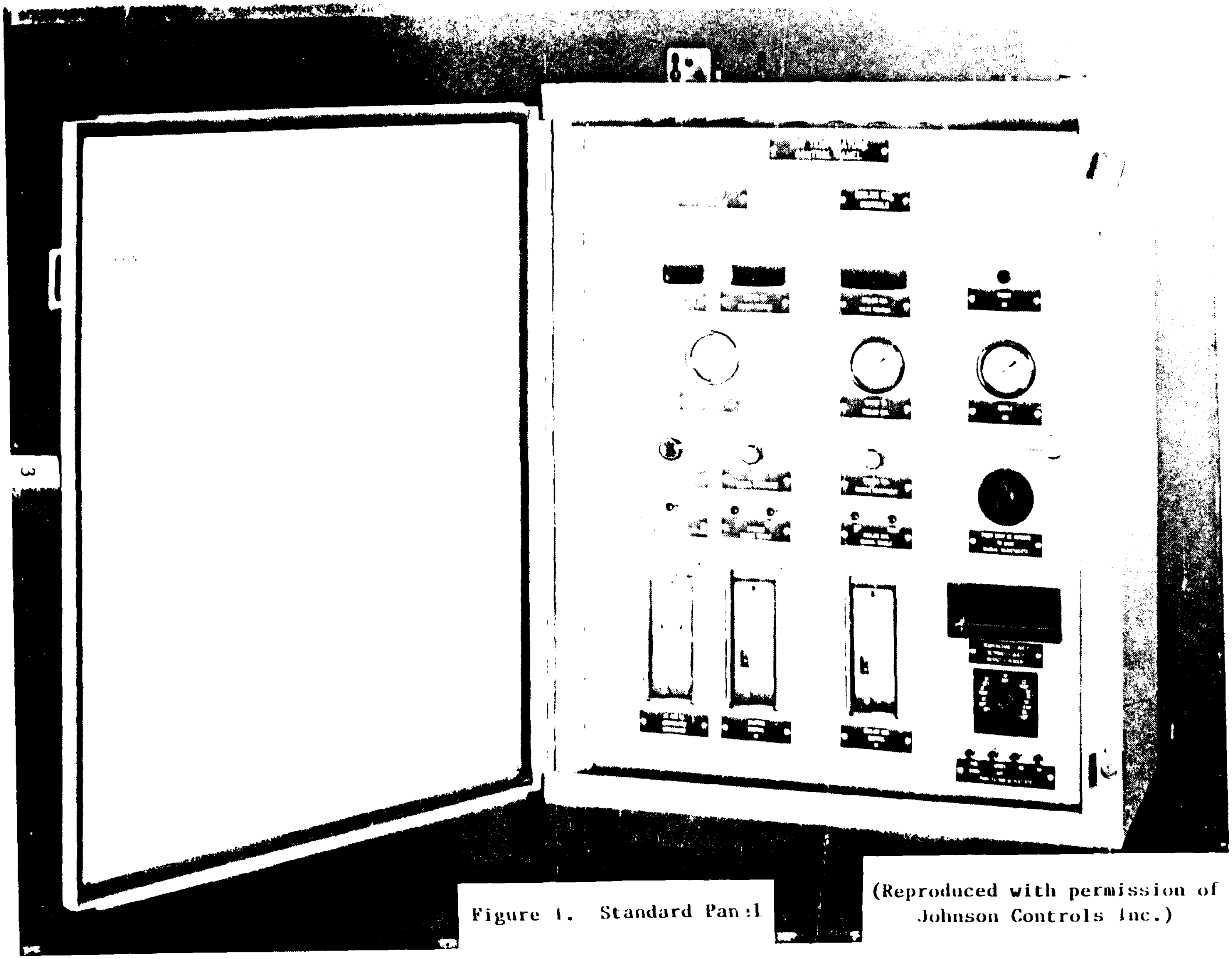


Figure 1. Standard Panel

(Reproduced with permission of Johnson Controls Inc.)

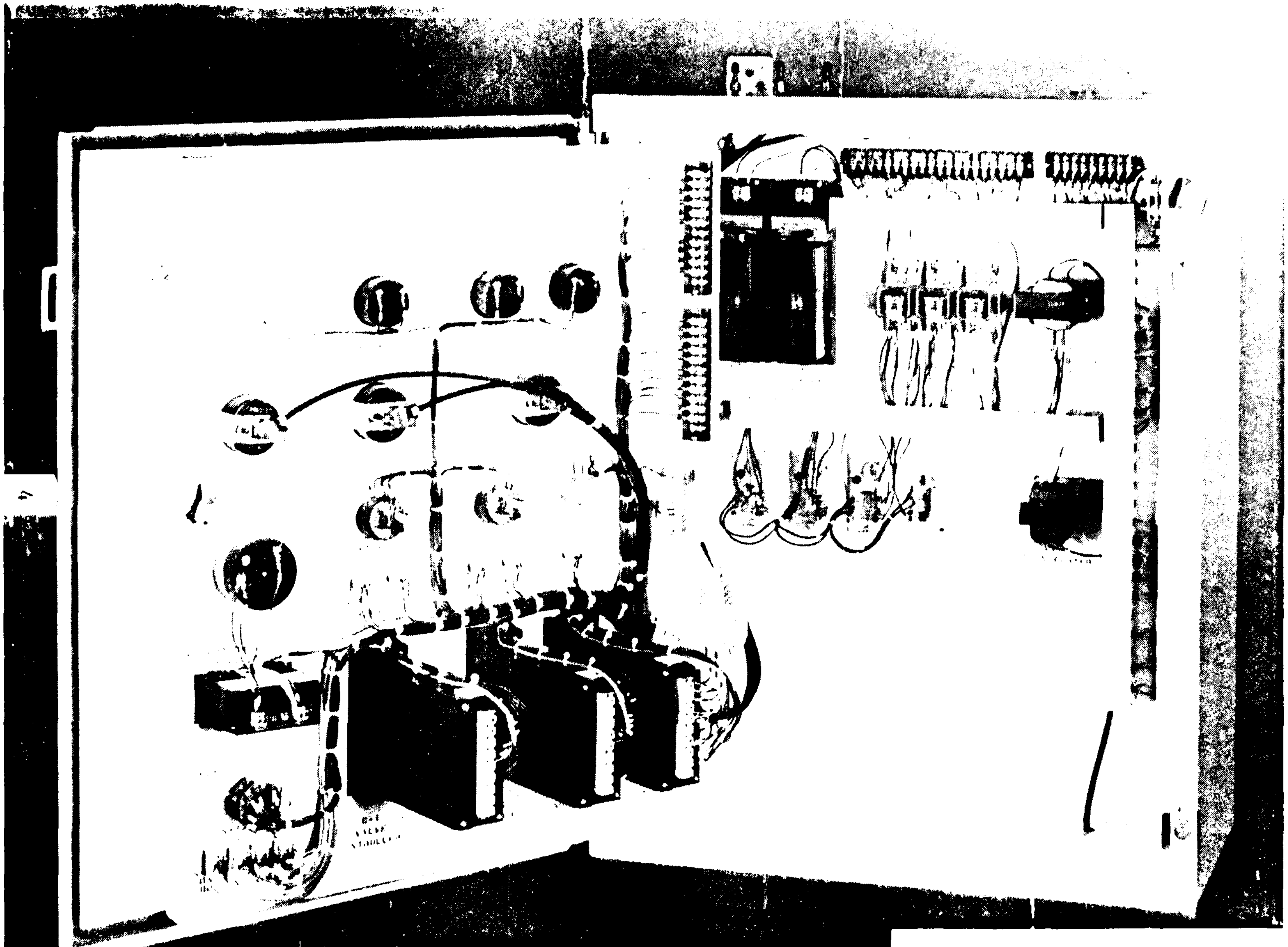


Figure 2. Standard Panel (Open)

(Reproduced with permission of Johnson Controls Inc.)

Scope and Limitations of Study

This research consisted of an experiment and a survey of experts using the Delphi technique. The experiment used a Johnson Controls Company Panel installed in parallel with a built-up system which used primarily Honeywell pneumatic components. The Panel and system components were not chosen because of the parent company. Instead, they were chosen based on availability and application. Indeed, some of the components in each of the systems are made by other well-known companies and others from generic parts. For further information concerning the exact system specifications, refer to the METHODOLOGY chapter.

It is possible that the experiment could be criticized for a lack of external validity. External validity "is concerned with the interaction of the experimental stimulus...with other factors and the resulting impact on abilities to generalize to (and across) times, setting, or persons" (Emory, 1985:118). While the ability to generalize about the entire population of control systems based on the results of one comparison may be limited, conducting a head-to-head comparison for extended periods of time in a field-test situation was certainly warranted. The experimental data added a degree of internal validity to the otherwise completely qualitative results.

Addressing the external validity concerns, expert opinions of individuals outside the realm of the experiment were solicited via a Delphi survey to improve the external validity of this study. "The Delphi method is a name that has been applied to a technique used for the elicitation of opinions with the object of obtaining a group response from a panel of experts" (Brown, 1968:3). The Delphi survey was limited to personnel directly involved with the Standard Control Panel. For the purposes of this study, "directly involved" was defined as participating in the development, design, installation, or maintenance of the Panel. Attempts were made to include persons with a variety of educational backgrounds because of the similar variety of individuals which will be exposed to the Panel throughout the Air Force. Because the Panel was only mandatory since July 1987, the number of persons directly involved was limited.

Definition of Key Terms

There are a few terms which must be defined to understand the work which follows.

First, a **pneumatic control system** is a control system which uses compressed air as its energy source. It consists of a series of diaphragms and switches which, depending on the temperature situation, either release or accumulate air, thereby moving controlled devices (valves or actuators). These devices permit or restrict the flow of a heating or cooling medium which air flows by as it goes to the space (customer's environment). (The air may already be in the space as in the case of radiators.) This air flows for the end purpose of maintaining a particular temperature in a room, a series of rooms, an entire building, or a complex of buildings.

Electronic control systems have the same function as pneumatics except electronics use direct current electricity as their energy source. They use electronic switches, sensors, and actuators. Their purpose -- heating or cooling a space -- and involvement of controlled devices are the same.

A **controller** is a component of a control system which accepts an input signal from a temperature sensor/ transmitter or other component, compares it to a local or remotely adjustable setpoint (the signal which should be coming from the component), and provides an output pressure or voltage to the controlled device. The output pressure or voltage is proportional to the difference between the setpoint signal (usually the desired temperature) and the sensed value (usually the actual temperature). This difference is called the error.

A **built-up system** is a control system composed of separate components, either pneumatic, electronic or a combination of pneumatic and electronic. Each component is mounted (on a board in proper installations or at various locations throughout the HVAC system in improper installations) and wires and pneumatic tubing connect the components. The separate components of a built-up system are as opposed to components already packaged and mounted which only require connections to the sensors and controlled devices as with the Standard Control Panel.

Finally, a **direct digital controller** is a computer which can be programmed to perform the same functions as either a pneumatic or electronic controller. It can be combined with either electronic controlled devices or pneumatic, using electronic-to-pneumatic transducers. Its purpose and relationship with sensors and controlled devices are the same as both the pneumatic and electronic controllers.

Research Objectives

The objective of this research is to determine if the Standard Control Panel meets the needs of the Air Force in terms of a reliable, useable control system which is easy to design, install and maintain.

Investigative Questions

The following questions were investigated: 1) How do the time required for and the difficulty level of design and installation of the Standard Panel compare with other controls systems? 2) How does the ability to maintain setpoint compare between the Panel and other systems? 3) How does the standard format of the Panel impact the ability of the technician to diagnose the HVAC system? 4) How does this diagnostics capability compare with the ability of a technician to diagnose via other systems?

Summary

To solve overcomplication and maintainability problems with HVAC controls, the Air Force directed the use of the Standard Control Panel for controls applications. This research used an experiment and a survey of experts to determine if the Panel would aid in solving the problems.

Outline of Research Design

The method consisted of two parts: an experiment and a solicitation of expert opinions using the Delphi technique. The researcher constructed an experiment to compare the difficulties encountered during the installation and operation of a Standard Panel with a built-up system. Both control systems operated the same HVAC system in Building 125 on Wright-Patterson Air Force Base. The built-up system was all pneumatic (air) components, except for the electronic time clock. Both systems (see Figure 3, Built-Up System and Figure 4, Standard Panel) were installed in September 1988. Specifically, the research compared Panel electronic sensors, mixed-air and cooling-coil controllers with pneumatic sensors and controllers from the built-up system. Both systems were designed to control pneumatic actuators. Since both systems could not control one HVAC system simultaneously, pneumatic switches were installed to divert control from the Panel to the built-up system and back again. Although only one system actually controlled the actuators at a time, the output signal was allowed to

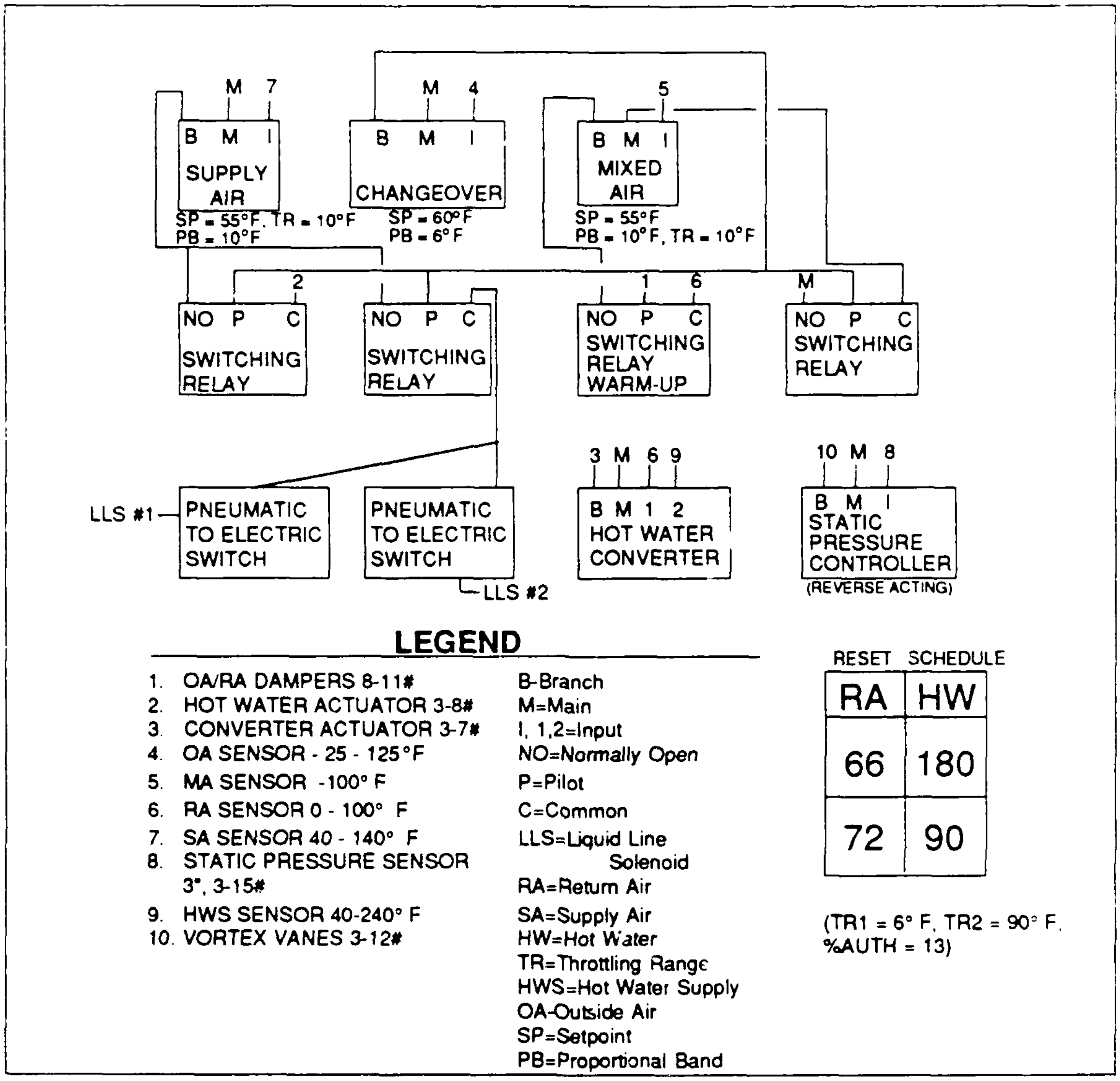


Figure 3. Built-Up System
(Schematic Drawing)

(Reproduced with permission of
2750th Civil Engineering Controls Shop)

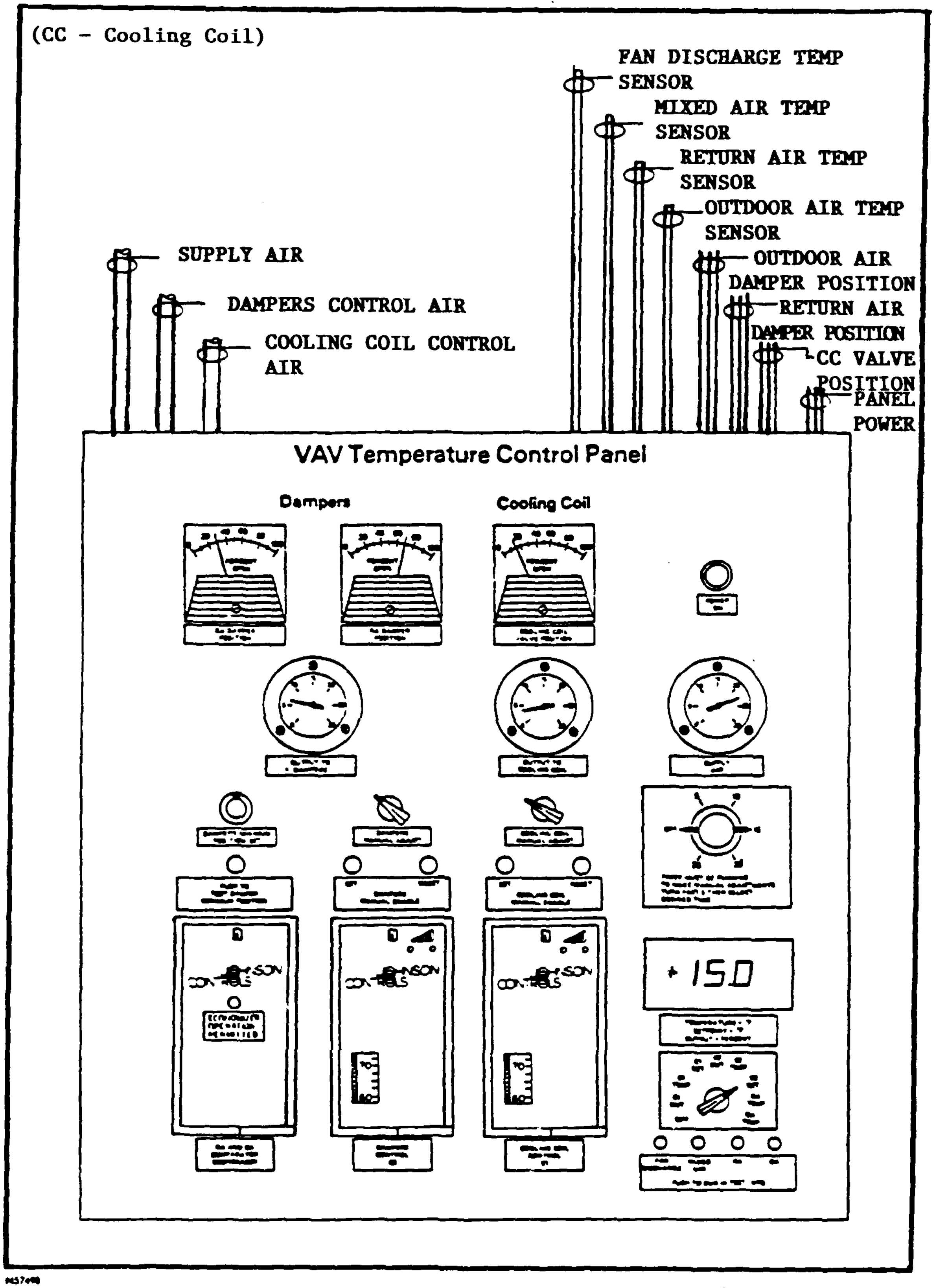


Figure 4. Standard Panel (Chostner, 1985)

(Reproduced with permission of Johnson Controls Inc.)

NOTES

1. FRONT PANEL LAYOUT FOR INTERIOR DOOR OF VAV TEMPERATURE CONTROL PANEL.

2. TEMPERATURE SENSORS TO BE FURNISHED BY OTHERS SHALL BE AS FOLLOWS:
   PLATINUM RTD, 4-WIRE
   100 OHMS AT 0^{o}C, ALPHA = 0.00385
   PER DIN43760 SPECIFICATIONS

3. TEMPERATURE SENSOR CABLE:
   4-WIRE SHIELDED CABLE WITH DRAIN WIRE
   1 EA. SHIELDED CABLE PER SENSOR

4. POSITION INDICATION INPUTS:
   3 EA. WIRES PER POSITION INDICATION INPUT

5. CONTROL PANEL POWER:
   117 VAC ± 10%
   HOT LEAD
   NEUTRAL LEAD
   GROUND LEAD

6. EMCS INTERFACE TERMINAL BOARD:
   THE FOLLOWING OUTPUTS ARE PROVIDED FOR AN EMCS INTERFACE:
   A. 0-10 VDC OUTPUTS:
      C1 OUTPUT 0-100%
      COLD DECK TEMP 0-100°F
      C1 SETPOINT 0-100°F
      C2 OUTPUT 0-100%
      MIXED AIR TEMP 0-100°F
      C2 SETPOINT 0-100°F
      RA TEMP 0-100°F
      OA TEMP 0-100°F
   B. 0-50 MICRO AMP OUTPUTS:
      CHWS VALVE POSITION 0-100%
      RA DAMPER POSITION 0-100%
      OA DAMPER POSITION 0-100%

DRAWING TITLE	REFERENCE DRAWINGS	NO	REVISION — LOCATION	DATE	BY
VAV TEMPERATURE CONTROL PANEL		3	REVISED NOTE 3 & 4	2-25-86	JDC
P/N: FSG5140-200		2	ADDED NOTE 6	1-16-86	JDC
		1	ADDED NOTE 2	11-13-85	JDC

SALES ENGR	APPLICATION ENGR	DRAWN
	JIM CHOSTNER	BY JDC DATE 7/24/85

PROJECT			CONTRACT NUMBER
	JOHNSON CONTROLS	**JOHNSON CONTROLS, INC.** FEDERAL SYSTEMS GROUP 1893 CRAIG ROAD ST. LOUIS, MO 63146 (314) 878-4646	DRAWING NUMBER

Figure 4. Standard Panel (Continued) (Chostner, 1985)

pass or was stopped by the switch. The signal from the sensors was still continuously sent to and processed by both control systems (see Figure 5). Installing pneumatic switches in the output lines instead of disconnecting the main power or the input signal meant that, although attempts were made to evenly distribute the amount of time each system actually controlled the system, reliability per functioning time was not affected by the switches.

The researcher also solicited expert opinions concerning the Panel via the Delphi technique. The personnel solicited had worked with the Panel from a variety of perspectives, from development through installation and maintenance. The first round of the technique was conducted via telephone interviews. The second round consisted of written correspondence and included a consolidation of the information gathered from the first round. The third round was also written and included a consolidation of all information gathered from round two. The purpose of obtaining these expert opinions was to reach a consensus concerning the design, installation, reliability and diagnostic capability of the Panels.

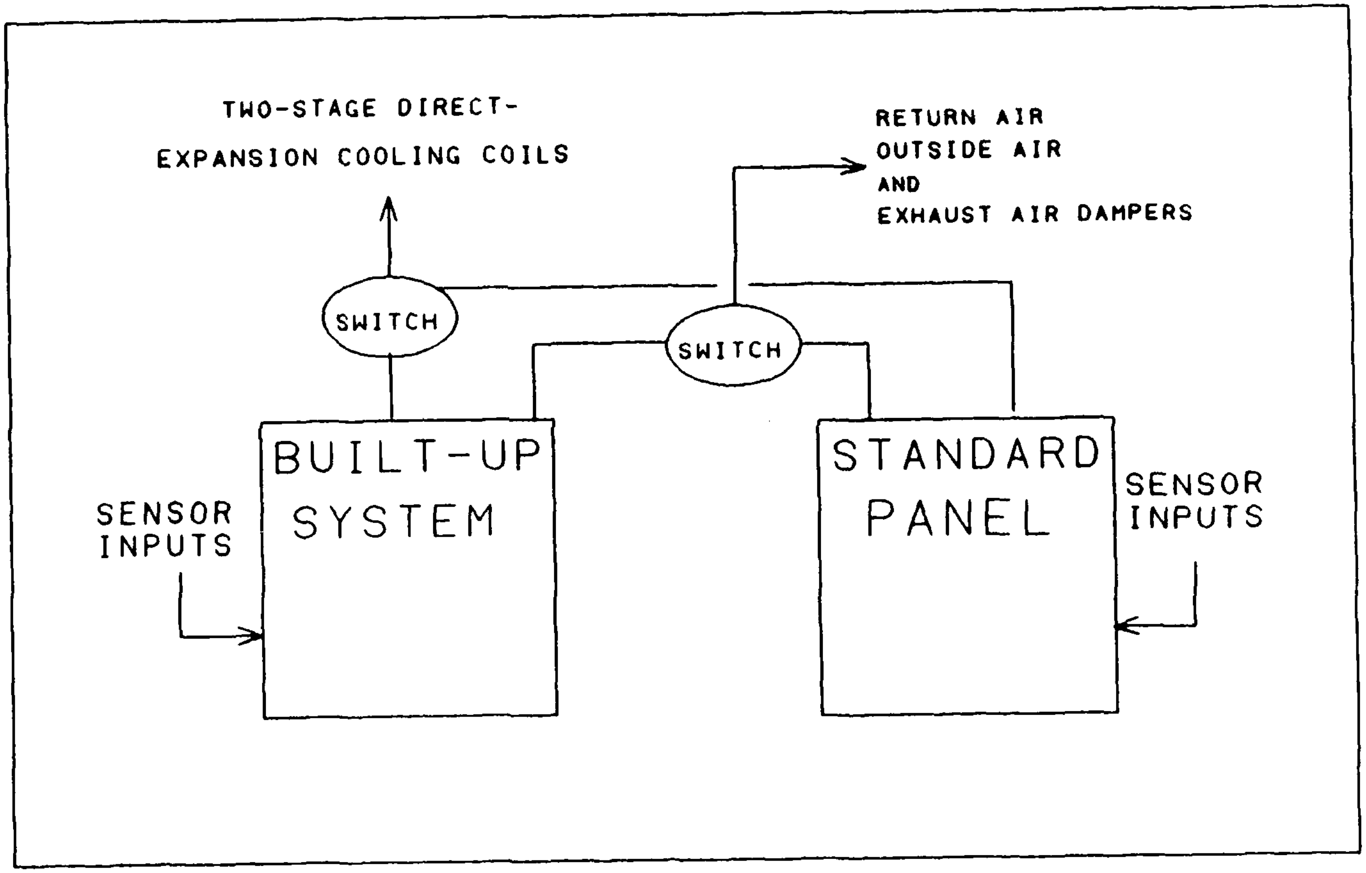


Figure 5. System Control Arrangement

II. Literature Review

Chapter Overview

In an effort to curb complication and maintainability problems with HVAC control systems, the Air Force distributed a letter in 1987 requiring the Standard HVAC Control Panel design be used for all existing projects which were 35% designed or less as of 22 July 1987 and for other projects where feasible (Flora, 1987:1,2). The reason cited in this letter for using this Panel is "ease of maintenance." Maintenance is a big part of the business of a Civil Engineering Squadron. This literature review will show that maintenance of mechanical systems, however, is a big problem.

The "ease of maintenance" of the Standard Panel is not because the parts which compose the Panel are new and revolutionary. The Panel is simply a combination of existing industry-grade control parts: electronic controllers and sensors with pneumatic actuators. The unique part of the Panel is the design. The components were specially chosen for reliability and were installed in standard locations within a Standard Panel. The unique part, then, is that it is standard.

This research covered various features of this Panel as compared to existing "built-up" or separate component systems and other control systems in terms of ease of design and maintenance and in terms of reliability and diagnostic capability. The literature on the Panel consists of opinions from Yandell and Hiller, an architect-engineering firm, and from a National Research Council (NRC) committee on Controls for Heating, Ventilating, and Air Conditioning Systems and will be presented in the Standard Panel section of this chapter. The existing controls research literature relating to this topic consists of information on and comparisons of the components which were possible candidates in the development of the Panel. Therefore, this review will first compare the chosen components with those that were not chosen and include a review of the need for such a Panel based on the weaknesses in the existing control systems in general. It will summarize advantages and disadvantages of using pneumatic, electronic, and direct digital control (DDC). Then, the opinions of Yandell and Hiller and the NRC committee will be presented. The theme to keep in mind throughout this review is the problem-solving sequence of events which led the Air Force to mandate the Standard Panel. First, the problem is described. Second, an analysis of the available options is performed. Finally, a solution is chosen.

The Problem -- Maintainability

New and innovative ideas from industry, with promises of substantial savings within short time periods, have brought the Air Force Civil Engineering (CE) community into an exciting world of high technology. In the air conditioning and associated controls area, CE has been bombarded with gadgets and wizardry by the industry. The military is not the only group in this situation, however. Roger Haines, a professional engineer and member of the HPAC (Heating, Piping, and Air Conditioning) board of consulting and contributing editors, included a letter from a reader in one of his articles. The writer was a civilian who was not employed by the Department of Defense, but the letter could have just as easily been written by an Air Force technician. The following are excerpts from that letter:

> Most control systems are too complicated for the average mechanic to understand....The attitude these days seems to be to add unnecessary "bells and whistles" to a system....This makes money for the manufacturer in the short run, but eventually budgets get cut and the mechanic in the building is forced to reduce the system to something he understands-usually a 2 by 4 stuck in the dampers....
>
> Documentation, when it exists, is often incomplete, misleading, inaccurate, or a combination of the three....I doubt that direct digital control (DDC) will prove to be the cureall [sic] it is being touted as. DDC can work, provided that the rest of the building systems work and, again, if the mechanics and operators don't break into a cold sweat when the word "computer" is mentioned.
>
> We have found that every time we add a piece of mechanized equipment, the skill levels of our mechanics must increase, and we are usually forced to hire more mechanics. Automation creates jobs for us. Any building owner who thinks that he can install a DDC system and lay off his stationary engineers is living in a fool's paradise that was created by the

unrealistic promises of the control companies. A DDC system may be operated by less able individuals who will be even more likely to disconnect dampers and jump out those components they don't understand [Haines, 1985a:146].

Overcomplication is a large and serious problem in the controls field, as indicated by the above letter. Technicians are overcome with advanced technology but do not know how to maintain it. In the Air Force, Major Steve Tom, a former instructor and Chief of the Mechanical Section at the School of Civil Engineering and Services at the Air Force Institute of Technology, addressed these problems as follows:

> No control system can be better than its maintenance. Even state-of-the-art computerized control systems are worthless if connected to dampers which are immobilized by rust. This may seem obvious, but many "energy conservation" programs pay far more attention to technology than to maintenance. Better maintenance of HVAC control systems represents the single most cost-effective program which many building owners can initiate, but it is also the most often overlooked....
>
> The list of woes which can beset control systems is almost endless. Calibration is a major problem, as are broken components, dirty supply air, burned out actuators, broken linkages, bad sensors and other similar ailments. Sometimes the people who are supposed to maintain these systems contribute to the problem. When a complaint is received they twirl knobs and bypass controllers until a trial-and-error solution is found. This may take care of the current complaint, but will almost certainly cause more problems than it cures.
>
> It is very easy for design engineers to complain of the terrible things which the maintenance crews do to control systems, but the truth is we are often as much to blame as they are. Unless we design maintainability into our control systems from the start, there is very little chance that they will be properly maintained. It is difficult to check the calibration of a mixed air controller, for example,

when the calibration data is not shown on the drawings and the controller itself is mounted on a duct 30 feet above the floor [Tom, 1985:38].

Civilian and military engineers have to make systems maintainable for technicians. The engineers cannot simply pass off bad designs and overlook poor maintenance policy and makeshift fixes. Not only are energy dollars lost by doing this because of inefficient systems, but the building users -- the customers -- suffer because of uncomfortable temperatures. If they suffer, that is where the real money, in production, is lost. For instance, an average employee receiving average pay and occupying an average amount of office space costs a company, or the government, approximately $250 per square foot per year. Compare that to the energy required to provide space conditioning to that employee, which costs between $1.00 and $2.50 per square foot per year (Int-Hout, 1986:529,533).

It can be seen that the energy cost, while significant, is small compared to employee costs (less than 1%). In fact, the best efforts to reduce energy consumption will be unlikely to reduce the energy costs by more than 10% to 15%, or less than 0.1% of employee salaries. In other words, if, in an effort to save energy employees are made uncomfortable and unproductive, money is lost instead of saved. "The function of a building is to provide a place in which people perform services. The most cost-effective building is the one with the highest productivity" (Int-Hout, 1986:529,533).

On one hand, maintenance is important, to the customers and to save money. On the other hand, it is not done because our control systems are too complicated. There is a limit on the amount of knowledge anyone, technician or engineer, can be expected to master. The complication of control systems has, in most cases, exceeded this limit. Therefore, maintainability has to go hand-in-hand with standardization and simplification. There are, however, many paths to standardization. Each path could be a particular type of control system. The path to the right may be totally pneumatic. Next to it may be totally electronic. The center path may be a mixture of pneumatics and electronics. To the left may be DDC. The question is, "Which path should be chosen?"

In the next section, the available paths will be described. The review will include the advantages and disadvantages of the various types of control systems available for Air Force use. The review will begin with the most basic control system, pneumatics, progress through electronics, and then DDC. After this review, the discussion will conclude with the current literature describing the Standard Control Panel, the Air Force's answer to a complicated controls world.

Pneumatic Controls

Advantages. Pneumatic controls are generally considered the easiest for technicians and engineers to understand. Air flow produces visual results and the components are connected via physical lines. Additionally, because of this familiarity, pneumatic controls have been used in most building HVAC systems (Hittle and Johnson, 1986:80).

Recently, however, pneumatics underwent a great deal of criticism and were frequently compared to state-of-the-art DDC systems. Some in the pneumatics industry quickly responded to that criticism stating, "Pneumatic control systems...are equally viable [as DDC] and are more cost-effective in most situations" (Asbill, 1984:111). C. M. Asbill is the Marketing Manager in the Control Systems Division of RobertShaw Controls Company. He bases this statement on his assessment of the comparison between pneumatics and DDC which is summarized in the following paragraphs.

The first advantage Asbill sees is that it is highly unlikely that any properly installed pneumatic control system will suddenly and completely "go down" requiring a manual override. Additionally, if there is trouble with the pneumatic system, it will usually only involve a single component, which is easy to spot and correct. The remainder of the system keeps working.

Secondly, concerning the statements that pneumatic control systems drift off setpoint but DDC systems do not, Asbill disagrees. If the compressed air supply is kept clean and dry, well-designed pneumatic controls will not drift off setpoint. He blames the "error" or drift cited in other articles not on pneumatic inaccuracies but on the use of proportional-only control where proportional plus integral (PI) control really should have been used. (For an explanation of proportional plus integral [PI] and proportional plus integral plus derivative [PID] control, see Doucet, 1982:70 or Asbill, 1984:113.) In the cited cases, it is actually offset, not drift, that is experienced. If PI control is used by good components, temperature changes as low as 0.02oF can be detected and control can be maintained within a degree.

The third advantage of pneumatic control components is that they are generally interchangeable among manufacturers, even internationally. If a building has a pneumatic system, according to Asbill, technicians are really not tied to one manufacturer to obtain replacement parts. With DDC, because of the proprietary nature of the components, they are.

Fourth, Asbill points out that pneumatic devices are also inherently explosion-proof. No electricity is required except to power the compressor, which can be isolated from the explosion-proof environment. On the other hand, electronic or DDC systems are not inherently explosion-proof. Making electronic controls explosion-proof is frequently as expensive as the controls themselves. In practically every case, an electronic control classified as explosion-proof is substantially more expensive than its standard (nonexplosion-proof) counterpart. For this reason, pneumatic controls are traditionally used in atmospheres requiring an explosion-proof rating. "Most hospital operating rooms, where potentially explosive vapors are present, use pneumatic...controls. Oil drilling platforms...also use pneumatic controls for the same reason" (Asbill, 1984:115).

Lastly, electrical interference, generated by radio transmissions, electric lines or even electronic control systems, does not affect pneumatic systems. This interference can, however, adversely affect electronic and DDC systems.

The bottom line, according to Asbill, is that in spite of claims to the contrary, there is no evidence that either DDC or pneumatic control systems are superior.

> To the best of our knowledge, no independent, certified, side-by-side tests have been run comparing DDC proportional to pneumatic proportional, DDC PI to pneumatic PI, or DDC PID to pneumatic PID. Without such comparisons, valid conclusions cannot be drawn. We can only rely on facts about both systems, and the facts indicate that DDC does not provide more precise control than pneumatic HVAC control systems [Asbill, 1984:112].

Concerning the future of pneumatic controls, Asbill foresees continued use. He predicts that today's efficient, state-of-the-art pneumatic controls will improve and will be used for years to come, probably indefinitely. "The improvements and new developments will not obsolete existing pneumatic systems but rather will complement them" (Asbill, 1984:115).

An additional advantage of pneumatic systems is the use of inexpensive, reliable actuators for valves and dampers (Hittle and Johnson, 1986:80-82). Their advantage over electric actuators is in cost and smoothness of operation. In fact, most DDC systems operate pneumatic actuators (Asbill, 1984:115).

Disadvantages. Larry Green, Senior Editor of Specifying Engineer, disagrees with Asbill and quotes Peter Hefferen, President of American Auto-Matrix, Inc., a manufacturer of DDC control systems, about pneumatic controls:

> "The vendors involved in pneumatics will see a reduction in business as pneumatic control rapidly becomes obsolete." He points to such indicators as the use of direct digital control... [Green, 1986:73].

Doctors Hittle and Johnson of the United States Army Construction Engineering Research Laboratory (USA-CERL) were also unconvinced of the reliability and accuracy of pneumatic controls so they conducted an experiment. They tested six brands of pneumatic temperature transmitters which are used as sensors in control systems for accuracy over their range of operation, 50-150 degrees Fahrenheit. They wanted to determine how well the measured output pressure conformed to the manufacturer's stated pressure temperature curve.

The results of their experiment did not favor pneumatics. They found one temperature transmitter to have a 2 psig output regardless of temperature. The others had output pressure errors which correlated with plus or minus 4 degrees Fahrenheit (Hittle and Johnson, 1986:80-82). Considering that the typical control system attempts to maintain the room temperature within 5 degrees Fahrenheit of the setpoint, errors in the sensor of 4 degrees either side of the setpoint do not contribute positively to this attempt.

CERL also tested the part which is normally at the heart of the pneumatic system, the receiver/controller, for accuracy or drift over a period of time. During these tests, CERL found the drift over a two-week period for the controllers which functioned to be plus or minus 2 degrees Fahrenheit. Other tested controllers were classified as "not functioning." These controllers had drift of plus or minus 7 degrees within 4 days.

CERL addresses other problems with pneumatic systems:

> First, they require a very clean source of supply air, dry and free of oil. While this may not be difficult initially to install a system with clean air, one mistake or failure, like overfilling the compressor with oil or failure of a compressor piston ring, can permanently foul the entire pneumatic system [Hittle and Johnson, 1986:80].

Pneumatic systems also require a constant source of supply air. Failure of this source to be continuous may result in "errors from 2 to 5 degrees Fahrenheit...at the control point within 24 hours after the supply air pressure has resumed" (Hittle and Johnson, 1986:82).

Electronic Controls

Advantages. Hittle and Johnson also analyzed electronic control equipment in the same April 1986 article. In describing electronic components, they wrote:

> Desirable characteristics of electronic controllers include high accuracy, a low temperature coefficient (changes in output caused by temperature change in the room housing the controller), a standard voltage range (0-10 VDC), good noise filtering, and easy access to Vset and Vtemp. Controllers with these characteristics are readily available and have been used routinely in process control applications [Hittle and Johnson, 1986:82,87].

An obvious advantage of electronic controllers noted here, and later in the article of electronic sensors, over pneumatic components is in long-term accuracy.

Disadvantages. CERL addresses no disadvantages of electronic controllers or sensors. However, they discuss the disadvantage of electronic actuators mentioned earlier.

> A potential disadvantage of the use of electronic controls is that electronic actuators are more expensive. Electronic actuators are usually also somewhat slower and may require more maintenance than pneumatic actuators. To avoid this problem [in composite systems], pneumatic actuators for valves and dampers can be used by interfacing these devices to electronic controllers through the use of electric-to-pneumatic transducers [Hittle and Johnson, 1986:87).

Even though CERL did not address them, the disadvantages of electronic components as compared to pneumatics as discussed by Asbill are worth reiterating. Specifically, one disadvantage is the tremendous additional cost of making the electronic systems explosion-proof. While pneumatic systems are inherently explosion-proof, electronic components require significant modifications which increase their cost. The other problem mentioned by Asbill is that electronic systems are also affected by and create electronic disturbances which alter system performance (Asbill, 1984:111,115). These disturbances may, depending on the severity, significantly affect the ability of the system to control.

Direct Digital Control

Advantages. According to Philip Doucet, one of the founders of Computer Controls Corporation, "Once you begin engineering control jobs with DDC, all the restrictions of poor accuracy, limited range, wear and aging, and inflexibility of mechanical controls are eliminated" (Doucet, 1982:66). Parameters of DDC systems can be easily changed at no cost even after installation. "When a setpoint is made, it will be maintained accurately without calibration. Controlled equipment will perform as desired" (Doucet, 1982:66). He also maintains that, if something goes wrong, the problem is remarkably easy o spot and repair.

Another advantage, according to Doucet, is that control loops can be reconfigured by just touching a few buttons. Rewiring controlled devices is no longer required. Reset schedules can be changed easily and no verification of the new schedule's performance is required. "The computer will respond with digital accuracy exactly as requested, quickly, all the time, under all possible combinations of internal and external environmental conditions" (Doucet, 1982:67).

The process of installing DDC is unique compared to traditional electronic or pneumatic systems. Once the DDC computer has been connected to the equipment, the computer can then accept analog and/or digital inputs. However, for the computer to know how to process these inputs, it must first be given instructions. These instructions are in the form of application packages, or software programs, with various control options and setpoints, all of which stay in the computer's memory. "The changeable portions of memory are what provide a user flexibility of control far greater than that available from mechanical control devices" (Doucet, 1982:68).

If a user wants to change the control characteristics, the process is very simple. Unlike pneumatic and electronic systems, a different computer is usually not required nor is any change to the input and output connections on the computer. By pressing a few buttons, the software enables the user to change control actions, gains, loop configurations, interlocks, limits, reset schedules, and other setpoints at any time, usually without interrupting normal system operation (Doucet, 1982:68).

One of the primary reasons people choose DDC is its reported expected energy and labor cost savings. By using PI and PID control, DDC can eliminate offset and reduce overshoot in control loops. This, plus maintaining setpoint adjustments that do not change with time, can save a significant amount of energy dollars. "Even the few degrees of temperature drift common with pneumatic controls, multiplied by total cfm [cubic feet of air per minute], represents sizable energy waste" (Doucet, 1982:68).

Another significant advantage of using DDC is that "Computers require no calibration or routine maintenance. Nothing ever needs to be readjusted, and DDC can even compensate for most normal wear in mechanical devices [actuators and dampers]" (Doucet, 1982:70).

Beyond the fact that DDC has no limited routine maintenance requirements, with DDC the computer can even be programmed to check its own performance. It can verify results of its own control actions and even signal either users or technicians monitoring the system via alarms when mechanical equipment fails. This helps pinpoint the cause of failure so a technician can be sent to repair the equipment with the proper tools (Doucet, 1982:70).

D. A. Coggan, a professional engineer and President of Coggan Douserv Associates, foresees yet another advantage of DDC. This advantage concerns design engineer involvement with DDC. "Although the DDC equipment is installed by one crew and put into operation by another, there is usually instant feedback if the slightest thing goes wrong" (Coggan, 1986:204). He thinks this instant feedback, a feature of only DDC systems, will force the designer to reevaluate the building operation and, hopefully, modify and improve his or her next building control designs. He also believes DDC forces design engineers to be much more aware of control system fundamentals than with traditional systems (Coggan, 1986:205). "Cut-and-paste" designs common in traditional pneumatic and electronic systems are much more difficult to do with DDC. The designer must know exactly what he or she wants the system to do and describe it accurately for the system to work properly. Although this is also true for traditional systems, the ability of the installer to "make it work" is much greater for an improperly designed traditional system than for a DDC system.

When DDC first emerged on the market, obtaining these advantages was a costly controls alternative. However, the decreasing cost of microcomputer and electronic components in general is making the DDC approach more desirable and more possible economically. This leads Haines to believe that "...some version of DDC will be the typical HVAC control system within the next decade" (Haines, 1983b:144).

Yandell and Hiller is an architect-engineering firm that was hired by the Air Force to analyze the future of DDC systems. They discuss their prediction for the future of DDC controls systems:

> The DDC industry is here to stay and expand. DDC controls techniques will gradually phase out all types of conventional controls, except in very special circumstances. The availability of "analog" controller products will, therefore, deteriorate and their prices escalate. The questions are not "if" but "when" and "how" the Air Force should make the transition to DDC [Yandell and Hiller, 1987:38].

They expect that 80% of the overall marketplace will convert to DDC by the year 2000. They also believe the Air Force should follow this industry trend (Yandell and Hiller, 1987:38).

Disadvantages. Asbill criticizes DDC controls as compared to pneumatics. He states that, although a pneumatic component may go down and affect a portion of the system, if a DDC system goes down, the whole system goes down because it is usually based on one computer. Additionally, he suggests that DDC may not be as accurate as claimed:

> There are many factors that can introduce inaccuracy to DDC systems, such as sensor error and changes in resistance at wire termination, sensor trim pots, and card edge-connectors. There are various transducers whose accuracy can change; there are electromagnetic influences on sensor wiring. Feedback pots and electric actuators are subject to wear and must be replaced. Extended power outages can cause loss of programming [Asbill, 1984:112].

He also suggests that new DDC companies may not be as reliable as pneumatic companies:

> Many DDC systems installed this year may be abandoned by their manufacturers and replaced by new ones in a few years, and some of the companies selling them will likely be gone or out of the controls business [Asbill, 1984:115].

According to Coggan, DDC systems also require more training than traditional systems. He thinks this training is lacking on all fronts, whether it be with the owner, contractor, engineer, or supplier, and will greatly impact system performance. For instance, a system purchased from the lowest bidder will lose its value if the supplier does not have a trained staff to properly install the system. Also, if the supplier makes mistakes or misinterpretations in programming, the result will, almost surely, be increased operating costs.

As another example, if the engineer writes system operating descriptions which are not totally comprehensive, the bidder will assume the least cost approach in order to get the job. Later improvements or corrections after the contract is awarded almost always mean unexpected extra costs. In addition, if the construction inspectors do not detect supplier or contractor misinterpretations, the system may not function as envisioned or desired.

Finally, most users or owners, including the Air Force, lack the comprehensive training needed, "...first, to understand control sequences that are being implemented, and second, to be able to make changes to the system programming without having to return to the supplier" (Coggan, 1986:205). For the Air Force, this lack of training means significant additional costs via service contracts.

Coggan concludes that major manufacturers are beginning to provide more and more training. In addition, training courses are being offered by independent sources (Coggan, 1986:205,206). The training still tends to be manufacturer specific, however. This means that, even if an engineer designs a good system, the manufacturer makes it correctly, the contractor installs it well, and the user is trained properly, for the Air Force, it is still just one system of many. Without standardization of design and components, it is very unlikely this exceptional design-to-training process will occur for all systems.

The major disadvantage most customers experience with DDC systems is not the possible total system failure, inaccuracies, company instability, or training. The most frequent complaint throughout the literature was that DDC systems have no common language, protocol, or set of procedures by which the user or technician can talk to the computer. Some companies have attempted to bypass this issue by making their language fairly simple. But each company still has essentially its own protocol and is unwilling to combine with another company for fear of giving away its trade secrets. The problem with this policy is that each of these protocols also has a considerable learning curve for the person attempting to learn the system. "Software is still a problem since protocol, message structure, and language vary greatly among manufacturers. `Mixing and matching' system elements is not simple" (Haines, 1983b:141,144). Haines does mention, though, that it is primarily at the software level that the problem exists. He says that, because most DDC units interface with electronic control devices at 4 to 20 milliamps or zero to 10 VDC, they are quite compatible at the hardware level (Haines, 1983b:141,144).

Yandell and Hiller expand on the differences in protocol in their report.

> Several of the controls companies have indicated that the development of industry standard protocols was not high on their list of product enhancement programs. We feel that this could change, given the right incentives, but now we are not optimistic about the development of a fast track schedule for such work. We would note that in recent months a few of the DDC-TCU manufacturers have offered to provide full disclosure on their communication protocols for this equipment [Yandell & Hiller, 1987:33].

Hefferen, in Green's article, reflects the opinions of both industry and the Air Force with the following statement.

> Large institutional owners and the government are looking for standards in communications methods and product performance. They don't want to be held captive to suppliers using proprietary protocols who won the first phase of a project and then use that success as a blank check for all subsequent phases [Green, 1986:73].

Doucet also discusses potential problems with the use of DDC and the accompanying software.

> It is a well documented fact in the computer industry that, over the life time of a software program, more money is spent fixing and modifying than in writing a program in the first place. This suggests that whether software is written or purchased, plans for long term support must be made. A building owner

> clearly cannot be locked into any custom software without experienced personnel to support it for the life of the system [Doucet, 1982:68].

He suggests that, if custom-written software is planned for the organization, a complete and thorough specification for capability and performance should be written. He also recommends checking with other customers of that vendor's software to solicit their opinions and recommendations (Doucet, 1982:68).

Because of the severe problem with so many programming languages, a great deal of industry is calling for standardization in DDC equipment. According to N. E. Prater, President and CEO of Mobay Corporation, a Pittsburgh-based manufacturer of chemicals and synthetics, "There must be a reversal of the current trend of today's distributed control systems to utilize only their own proprietary communication protocol" (Prater, 1987:29). This will allow businesses which have many buildings, each with a particular system, to integrate them and still permit information flow. This is especially important for the Air Force since it is essentially required to accept the lowest bidder in construction contracts. Currently, this lowest bidder may or may not have the same DDC system as in the other buildings. If not, communication between his system and others is not possible. If all systems had a standard protocol, however, it would not matter what type the lowest bidder installed. All systems would be able to transfer information to each other. "We need non-proprietary, multi-vendor, international standards and the products that go with them if we are to reduce both costs and risks to an acceptable level" (Prater, 1987:29). Standardization will not only help the users, i vill enable manufacturers to mass produce equipment and compete on a world-wide basis. The idea of standardization is readily accepted by those in the controls world. The stumbling block is in <u>how</u> to best implement it (Prater, 1987:29).

The Standards Committee of The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) answered the customers' calls, took the first step and approved the formation of a special project committee aimed at defining a standard communications protocol for energy management systems.

> A standard protocol, if incorporated by manufacturers into their EMS systems, would allow users who are configuring multiple EMS installations to link equipment from different vendors, and would facilitate shared monitoring and control between different vendors' EMS....[They believe] a standard could probably be developed in one to three years [Racanelli, 1987:1,7].

Prater disagrees with the time frame for the standardization. In an article by Patricia Raffaele, he is quoted as saying, "...because of the proprietary nature of product development in the controls industry, it will be at least 10 to 15 years before an international standard protocol is developed" (Raffaele, 1987:1).

CERL also investigated the advantages and disadvantages of DDC and reported the findings of their research in their 1986 article. They concluded that, while DDC seems like the alternative for the future, it is not currently recommended because:

- Hardware reliability has not yet been established.

- Programming DDC units is difficult and requires skills beyond the capabilities of most maintenance staff. This problem is made worse by the lack of standard programming languages.

- Most DDC control systems marketed by HVAC control companies perform all fan system control functions with one microprocessor. A hardware or software failure usually results in complete loss of control. It is almost always impractical to repair a DDC unit in the field; recovery from a failure can be difficult, time- consuming and expensive.

- At present, DDC costs are high and are only competitive with analog systems when the local controllers are part of a larger central energy management and control system.

- Standard DDC offerings do little more than analog control systems. Indeed, it is not clear that more powerful control schemes are needed. Both the potential benefits and the practicality of more powerful computer based control methods remain to be demonstrated [Hittle and Johnson, 1986:92,93].

After a DDC system is installed, problems may also occur. If the problem can be found by the technician, fixing these problems usually involves "...replacing or recalibrating a control device, replacing a defective 'board' [or panel] in the DDC, [or] modifying the software" (Haines, 1985b:128).

There is also a possible problem with DDC panels if the power goes out. If the memory in the system is volatile, it is lost with the power and must be restored again from another source when the computer is restarted. Even with a nonvolatile memory, a sudden power loss may result in some scrambled data. This can be avoided if the system has a battery backup to allow an orderly shutdown in case of power loss (Haines, 1983a:89).

Currently, the problems with DDC led the Air Force to impose a moratorium on the use of direct digital control except on approved projects. This policy is documented in Engineering Technical Letters (ETL) 83-7, 1110-3-354, and 86-16, and Change Order Number 1 to ETL 83-1 (Yandell & Hiller, 1987:4).

Prior to the Air Force moratorium on the use of DDC, Tactical Air Command (TAC) installed a large number of systems throughout the command. According to Jerry Williams, HQ USAF/LEEEU, TAC is now paying between $250,000-$275,000 a year on service contracts to maintain their systems because no one at base level can maintain them and the replacement panels are so expensive (Williams, July 1988).

Major Tom summarizes the current Air Force perspective with the following statements:

> This [DDC] approach works very well when applied to a single building or a group of buildings with one manufacturer's control system, but it causes severe problems when applied to hundreds of control systems, each of which was purchased from the least cost bidder.

> No matter how "user friendly" a programming language is, it will be frustrating for someone who has to use 20 or 30 different languages on a daily basis. This problem is compounded by the frequent rotation of military personnel between bases. Air Force personnel must be prepared to deploy to any base in the world and operate from that base, a tasking which includes operating the HVAC systems. We cannot retrain these people every time they encounter a new control system so we must rely on simple, straightforward designs which do not rely on any one manufacturer's products [Tom, 1985:39].

The Hybrid System -- The Standardized Control Panel

The previous discussion concerned a number of problems with components currently in the controls inventory and reviewed many advantages common with the various systems. Through CERL, the Air Force chose from the possibilities -- pneumatic, electronic, DDC or a combination -- what they deemed "the cream of the crop." This was a combination of components -- electronic controllers and sensors with pneumatic actuators -- with high-grade specifications, using a Standard Panel. It was this system that the Air Force made mandatory.

This section describes the advantages and disadvantages of the Panel found in the literature.

Advantages. CERL believes that, to perform successfully, an HVAC control system must be "...well-designed, use high quality hardware, and employ simple, efficient control strategies. Clear descriptions of system and methods must be provided" (Hittle, 1986:243). CERL Energy Systems (ES) researchers designed a number of

Standard Panels that incorporate standard control strategies to meet these requirements. These Air Force (CERL) Standard Control Panels are "...simple, efficient, factory-calibrated control panels that can be retrofitted onto existing HVAC units" (Hittle, 1986:243). If done properly, this changeover from existing to new control systems can be made with almost no downtime. In addition to exceptional performance, CERL believes that standard designs facilitate fabrication, thereby reducing costs. Standard designs also allow development of more comprehensive operation and maintenance documents.

The components chosen by CERL for their Panel have been carefully tested and selected for their high quality and proven efficiency and reliability. CERL also designed their Panels to include all the diagnostic equipment a technician might require to analyze the system. Included in the equipment is a built-in voltmeter which has a selector switch to display temperatures, setpoints, and controller outputs. The Panel also has push-to-test buttons which let operators quickly identify defective components. Additionally, because of the Panel's modular construction, these defective components can be replaced easily. The control units and diagnostic displays are arranged logically on the front Panel, thereby making the system easier to operate. The most advantageous aspect of the Panel is that the various Panel designs (for various systems) use similar principles of operation, which makes it easy to learn to operate different types of Control Panels. Ideally, if the Panels are eventually installed in all applicable locations Air Force-wide, the technician will already be familiar with the system and the locations of various components within the Panels when investigating a new system. This should make system analysis, maintenance, and repair significantly easier. Lastly, the Panels are tamper-resistant, with all parts concealed behind a lockable door which is part of the heavy, metal enclosure (Hittle, 1986:243).

To complement the components of the Panel itself, pneumatic actuators were chosen as the controlled devices. Referring to the advantages previously discussed concerning pneumatic actuators, it was determined that pneumatic actuators are superior to electronic actuators in terms of performance and cost (Hittle and Johnson, 1986:80-82).

"Results so far suggest that USA-CERL's HVAC control panels can save up to 25% of heating and cooling costs" (Hittle, 1986:243). Hittle believes this figure would be larger if savings in maintenance and repair could be quantified and compared to other, less reliable systems. He also believes the installed cost for the panels could be even lower than field-constructed pneumatic systems (Hittle, 1986:243).

Previously, it was noted that CERL designed several Panel types for various applications. These include the following:

a. Static Pressure Control Panel for Fan Speed Control (FSC) System

b. Static Pressure Control Panel for Inlet Vane Damper (IVD) System

c. Variable Air Volume (VAV) Temperature Control Panel

d. Hot Water Temperature Control Panel

e. Temperature Control Panel for Single Zone System with one Controller

f. Temperature Control Panel for Single Zone System with Cascade Control

g. Temperature and Humidity Control Panel for Single Zone System

h. Multizone Control Panel [Yandell & Hiller, 1987:5].

Summarizing, CERL says,

> The control system with panel emphasizes several important design considerations: (1) simplicity, (2) reliability, (3) maintainability, (4) accuracy where accuracy is needed, (5) appropriate use of PI control, (6) use of high quality components where needed, and (7) use of standard sensors and signals provide simplicity and interchangeability.
>
> If the above control system is accompanied by very specific and clear operating and maintenance instructions (a faded blue line drawing on the wall will not do), it should provide efficient, accurate, and reliable control for many years without recalibration of the temperature sensors or any of the electronic controllers [Hittle and Johnson, 1986:92].

Disadvantages. Yandell and Hiller are not as excited about the standardized Control Panel as CERL. In their report, Yandell and Hiller state, "...the use of this type of panel will not become commonplace throughout the controls industry" (Yandell and Hiller, 1987:6). They base this on their belief that electronic PI analog controllers are being phased out and will be replaced by DDC in the next few years. They also believe that the Air Force's energy management and special operating strategies make the Panel more complex and essentially limit its demand to the Department of Defense (Yandell & Hiller, 1987:6).

Overall, the idea of standardization is favorable to Yandell and Hiller.

> The problem is that the nominated technology will become steadily outdated as time passes. Therefore, the question is can equivalent standards be developed to allow the Air Force to use the digital processor and DDC techniques towards which the controls industry appears to be moving and is appropriate to the Air Force's requirements? Such DDC panels could be operated individually, as a direct replacement for the Air Force standard panel, or integrated into an on-line network if they are the product of the same manufacturer....It should be noted, however, that the sophistication of many of these packages far exceeds the facilities incorporated into the present Air Force standard panels and, therefore, their requirement for Air Force application would have to be reviewed on an individual project basis [Yandell and Hiller, 1987:6].

Another possible problem with the Panels is that the controls are not interchangeable, i.e., cannot be replaced with a component from another manufacturer. The ETL which mandated their use also requires replacement with the same make and model as the original, thereby forbidding the interchanging of parts. The theory behind the ETL is that standardization will severely limit the need to interchange parts.

Despite the mandatory letter requiring Air Force Standard Panel use and in spite of all the advantages, their use is not commonplace. Contractors continue to make value engineering proposals for something different and bases continue to accept the proposals (Williams, July 1988).

The argument against standardization was supported by the 1988 National Research Council (NRC) Report on Controls for Heating, Ventilating, and Air Conditioning Systems. Among their recommendations are the following:

> a. Agencies should modify their directives to HVAC consulting engineers to encourage them to propose the use of systems and requirements that differ from agency design criteria and guide specifications whenever they believe the government would benefit.
>
> b. Agencies should establish mechanisms for quickly reviewing and acting on requests from consulting engineers for waivers from the provisions of published design criteria and guide specifications.
>
> c. Agencies should adopt the practice of reviewing and updating HVAC design criteria and guide specifications annually to incorporate recent changes in control technology [NRC, 1988:5].

In addition to their position against standardization in general, the committee also had specific reservations about using the Panel. These reservations were totally based on the members' experience and judgment and included the following: 1) The agency could not enforce any warranty against a contractor who was forced to conform to such rigid requirements as those required for Panel construction and installation. 2) The standard systems have a much higher first cost. 3) The savings in maintenance costs may not be as significant as expected due to manufacturer differences. 4) The cost to keep required design manuals and guide specifications up to date might be prohibitively high (NRC, 1988:36-37).

Conclusion

The consolidation of literature in this chapter presented an analysis of the current HVAC controls situation as it pertained to the Air Force. This analysis began with the serious requirement to maintain our systems. The literature concluded that, in many cases in the civilian world and in the military, systems were not adequately maintained. The reasons for not performing the maintenance were many, the most common of which was overcomplicated systems. From the standpoint of the Air Force on this issue, the way to avoid complication is to standardize. The question then was, of the many types of controls systems to choose as the standard, which one is best for Air Force applications? The choice required analysis of the advantages and disadvantages of the three types of systems -- pneumatics, electronics, and direct digital control.

In the analysis, it was determined that pneumatic system sensors and controllers tend to lean toward inaccuracy but their actuators were superior to electronic in the same cost range. Following the discussion of pneumatics, the literature found that electronic systems were very accurate as compared to pneumatics, but the cost of actuators comparable in quality and performance with pneumatics was considerably higher. Next, during the review of direct digital control (DDC), it was determined that, while DDC possesses superior accuracy and flexibility, the complication and lack of standardization have led to an Air Force moratorium on its use.

Since the Air Force could not pick one sole system type to use for our standardization and still get the best, they chose not to use DDC and instead to mix electronic controllers and sensors with pneumatic actuators for the design system. It is this system, with specific attention given to the Control Panel, on which this research was done. The research concentrated on maintainability of this Standard Panel system compared with other control systems and asked the following questions: Is an HVAC control system easier to design and maintain than other control systems? Is a Standard Panel system more reliable than other control systems? To make the comparison between the systems, an experiment and a survey of expert opinions using the Delphi technique were done. Chapter III, the METHODOLOGY chapter, will describe the methods of this research in detail.

III. Methodology

Chapter Overview

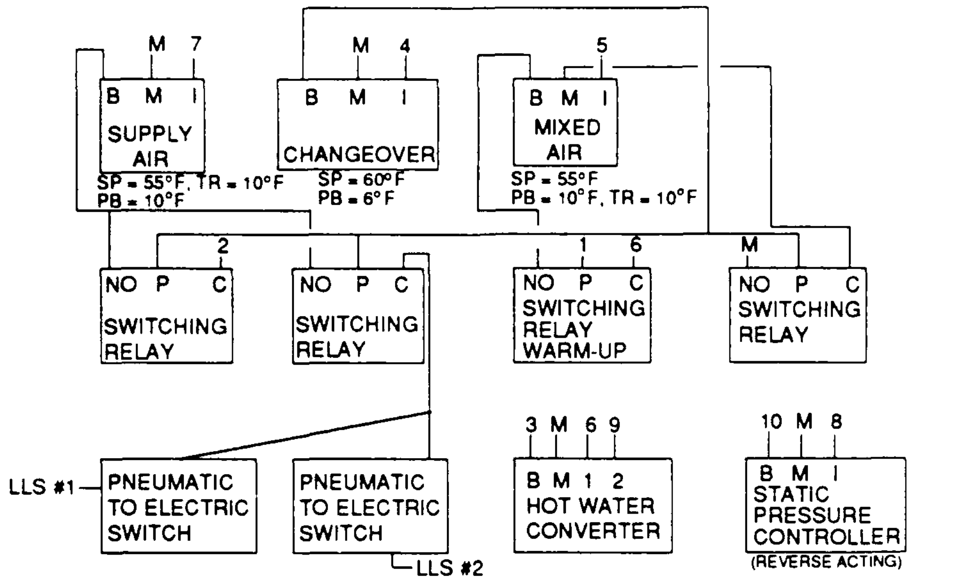
Chapter I discussed the current problems in the HVAC controls industry. One of the largest problems was control system maintainability. The chapter also discussed the need for standardization which led to the mandatory use of the Air Force Standard Control Panel for Air Force installations.

Chapter II traced the decision-making process involved in the selection of components which compose the Standard Panel and included the small amount of literature available on the Panel itself.

Both chapters mentioned the need for testing the Air Force's assumption that the Panel will solve the controls problems. This research performed that test, using an experiment and a Delphi method survey of experts in a thorough investigation of the Panel's performance capabilities and weaknesses. This chapter, the METHODOLOGY chapter, will outline the specific methods used to compare the Standard Panel system with other control systems and analyze the data and the method of extracting information from the experts.

Research Method I -- Experiment

The researcher constructed an experiment to compare the difficulties encountered during the installation, calibration and operation of the Standard Panel with those of a built-up system. Both control systems were installed and operated the same HVAC Variable Air Volume (VAV) system in building 125 on Wright-Patterson Air Force Base. The built-up system was totally pneumatic (air) components, except for the electronic time clock. The components of this built-up system were replaced with new or rebuilt components by the Civil Engineering Controls Shop in September 1988 (see Figure 6, Built-Up System). The new Panel and new sensors were installed by the researcher in September 1988 (see Figure 7, Standard Panel). Specifically, the research qualitatively analyzed installation and calibration procedures during Panel installation according to the United States Air Force Standardized HVAC Control Systems-Technical Specifications (United States Army Construction Engineering Research Laboratory, 1987:1-53). Design and installation of all types of Standard Panels are based on these specifications. Operational data was then collected from November 1988 to May 1989 to compare the reliability of Panel electronic sensors, mixed-air and cooling-coil controllers with pneumatic sensors and controllers from the built-up system.



LEGEND

1. OA/RA DAMPERS 8-11#
2. HOT WATER ACTUATOR 3-8#
3. CONVERTER ACTUATOR 3-7#
4. OA SENSOR - 25 - 125°F
5. MA SENSOR -100° F
6. RA SENSOR 0 - 100° F
7. SA SENSOR 40 - 140° F
8. STATIC PRESSURE SENSOR 3", 3-15#
9. HWS SENSOR 40-240° F
10. VORTEX VANES 3-12#

B-Branch
M=Main
I, 1,2=Input
NO=Normally Open
P=Pilot
C=Common
LLS=Liquid Line Solenoid
RA=Return Air
SA=Supply Air
HW=Hot Water
TR=Throttling Range
HWS=Hot Water Supply
OA-Outside Air
SP=Setpoint
PB=Proportional Band

RESET SCHEDULE

RA	HW
66	180
72	90

(TR1 = 6° F, TR2 = 90° F, %AUTH = 13)

Figure 6. Built-Up System (Schematic Drawing)

(Reproduced with permission of 2750th Civil Engineering Controls Shop)

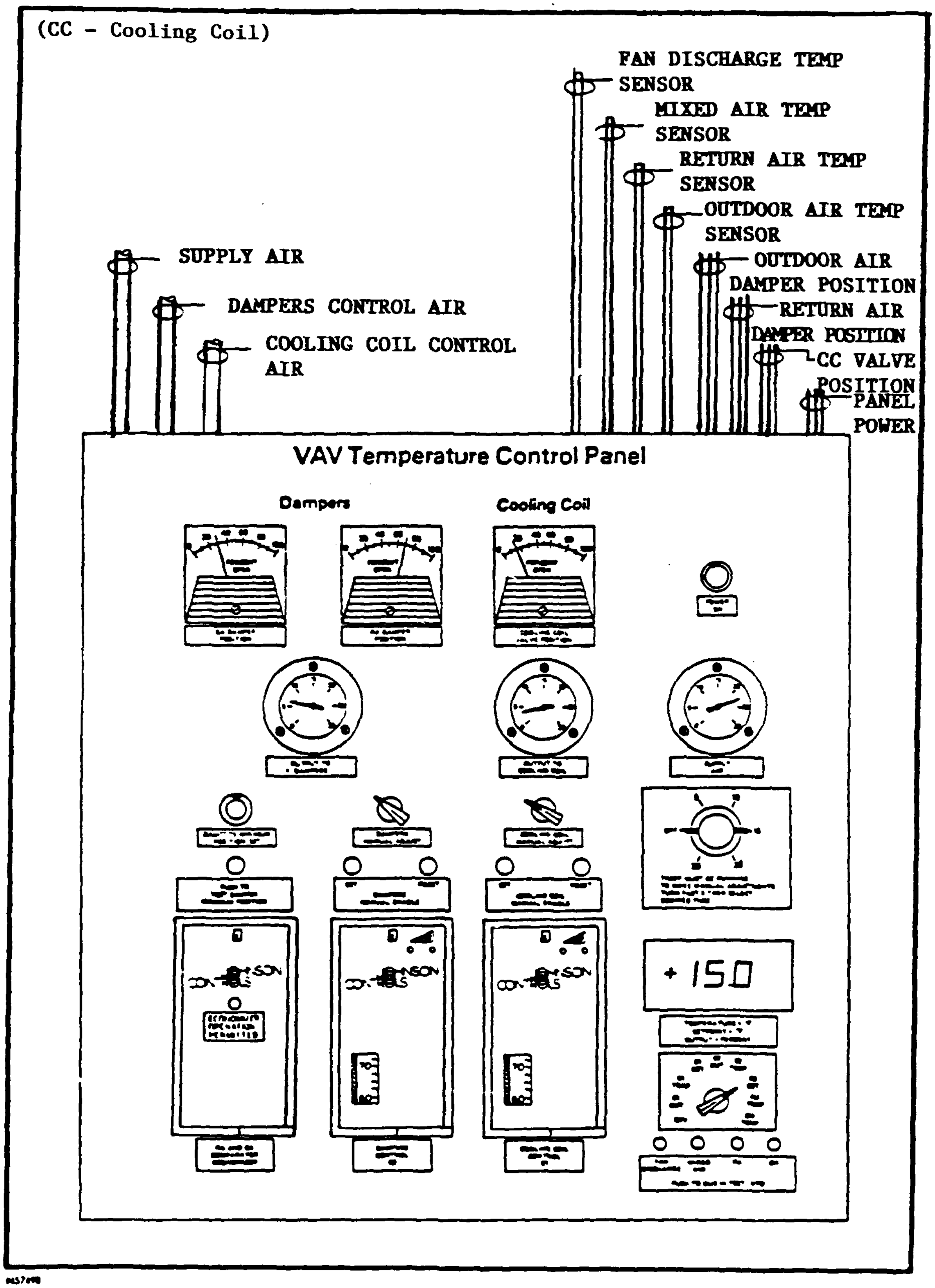


Figure 7. Standard Panel (Chostner, 1985)

(Reproduced with permission of Johnson Controls Inc.)

NOTES

1. FRONT PANEL LAYOUT FOR INTERIOR DOOR OF
   VAV TEMPERATURE CONTROL PANEL.

2. TEMPERATURE SENSORS TO BE FURNISHED BY
   OTHERS SHALL BE AS FOLLOWS:
   PLATINUM RTD, 4-WIRE
   100 OHMS AT 0°C, ALPHA = 0.00385
   PER DIN43760 SPECIFICATIONS

3. TEMPERATURE SENSOR CABLE:
   4-WIRE SHIELDED CABLE WITH DRAIN WIRE
   1 EA. SHIELDED CABLE PER SENSOR

4. POSITION INDICATION INPUTS:
   3 EA. WIRES PER POSITION INDICATION INPUT

5. CONTROL PANEL POWER:
   117 VAC ± 10%
   HOT LEAD
   NEUTRAL LEAD
   GROUND LEAD

6. EMCS INTERFACE TERMINAL BOARD:
   THE FOLLOWING OUTPUTS ARE PROVIDED FOR
   AN EMCS INTERFACE:
   A. <u>0-10 VDC OUTPUTS</u>:
      C1 OUTPUT 0-100%
      COLD DECK TEMP 0-100°F
      C1 SETPOINT 0-100°F
      C2 OUTPUT 0-100%
      MIXED AIR TEMP 0-100°F
      C2 SETPOINT 0-100°F
      RA TEMP 0-100°F
      OA TEMP 0-100°F
   B. <u>0-50 MICRO AMP OUTPUTS</u>:
      CHWS VALVE POSITION 0-100%
      RA DAMPER POSITION 0-100%
      OA DAMPER POSITION 0-100%

DRAWING TITLE

VAV TEMPERATURE
CONTROL PANEL

P/N: FSG5140-200

REFERENCE DRAWINGS	NO	REVISION — LOCATION	DATE	BY
	3	REVISED NOTE 3 & 4	2-25-86	JDC
	2	ADDED NOTE 6	1-16-86	JDC
	1	ADDED NOTE 2	11-13-85	JDC

SALES ENGR

APPLICATION ENGR
JIM CHOSTNER

DRAWN
BY JDC DATE 7/24/85

PROJECT

JOHNSON CONTROLS, INC.
FEDERAL SYSTEMS GROUP
1893 CRAIG ROAD
ST. LOUIS, MO 63146
(314) 878-4646

CONTRACT NUMBER

DRAWING NUMBER

Figure 7. Standard Panel (Continued) (Chostner, 1985)

Both systems are designed to control pneumatic actuators. However, since both systems cannot control one HVAC system simultaneously, pneumatic switches were installed to divert control from the Panel to the built-up system and back again (see Figure 8, System Control Arrangement). These switches allowed air to pass to two groups of pneumatically-controlled actuators. One group of actuators opened and closed outside air, return air, and exhaust air dampers to maintain a set mixed-air temperature. The second group opened and closed solenoid valves of a two-stage, direct-expansion cooling-coil system. Although only one system actually controlled the actuators at a time, it is the output signal which was allowed to pass or was stopped by the switch. The signal from the sensors was still continuously sent to and processed by both control systems. Installing pneumatic switches in the output lines instead of disconnecting the main power or the input signal meant that, although attempts were made to evenly distribute the amount of time each control scheme was actually controlling the HVAC system, reliability per functioning time was not affected by the switches.

The Standard Panel system consisted of the following components:

Panel: Johnson Controls Variable Air Volume Temperature Control Panel

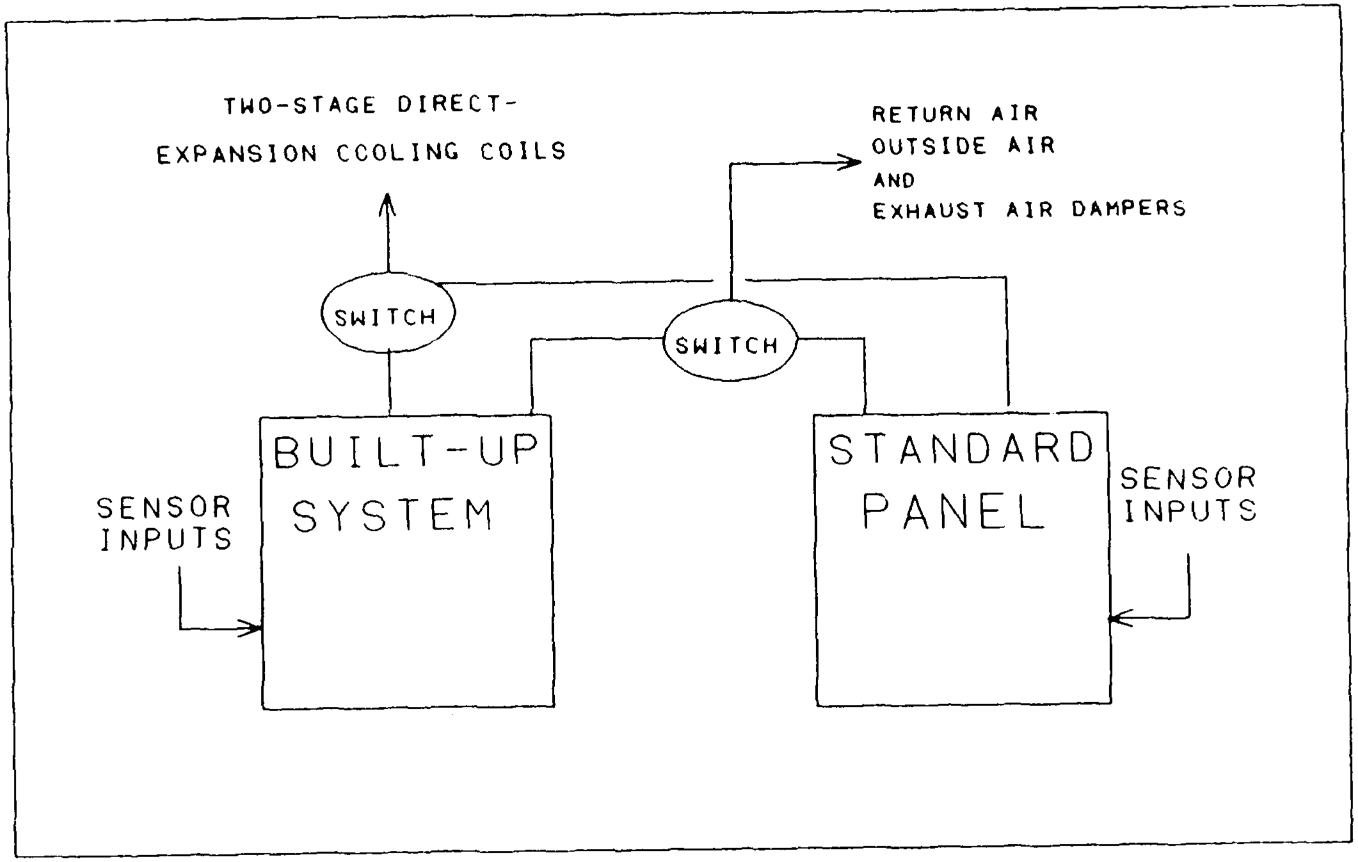


Figure 8. System Control Arrangement

Sensors: Platinum Resistance Temperature Detector (RTD) Precision Sensing Element. 100 Ohms at 32 degrees Celsius, Temperature Coefficient of 0.385% per degree Celsius.

Damper Position Indicators: 500 Ohm Variable Circular Resistors

Wire: Five-wire twisted cable and four-wire shielded cable

The built-up system consisted of the following components:

Controllers: Honeywell RP908 and RP920D Pneumatic Controllers

Sensors: RobertShaw T150 Pneumatic Temperature Sensors

Time Clock: Grasslin Digi 127

Switching Relay: Honeywell RP471

Warm-up Relay: Honeywell RP670

Static Pressure Sensor: RobertShaw 1-3 inches (Changed in December 1988 to a Honeywell RP920D, TR = 1, %Xp = 14, %w1 = 6)

Pneumatic-Electronic Relay: Barber-Coleman

In addition to the above components, pneumatic tubing and electrical wire for purposes other than sensors were required.

Both qualitative and quantitative analyses were done as part of the comparison. The researcher conducted a qualitative analysis of the installation procedures, calibration procedures, ability to diagnose the HVAC system via the Panel, and overall capability of the system to perform its intended function. Where documentation was available in the USAF Standardized HVAC Control Systems Technical Specifications or installation instructions from Johnson Controls (see Appendix A), it was used during installation, calibration, and analysis.

Additionally, a quantitative analysis of drift from setpoint and calibrated output was made. This analysis made use of time series analysis (Kachigan, 1986:Ch 18) to establish a difference between the reliability of the two systems. The details of the comparison procedures are outlined in the HYPOTHESIS and TEST STATISTIC sections.

Research Method II -- Delphi Technique

The researcher also solicited expert opinions concerning the Panel via the Delphi technique.

> Briefly, the Delphi Method involves surveying a group of experts for their anonymous ideas and judgments concerning a specific problem or situation. These judgments are then pooled and summarized by a staff group and then returned to the participants. The experts reevaluate their positions on the problem and again respond to the survey questions. After a few rounds of this, a consensus judgment is constructed, one that may become a critical input to the decision process [Brown and Moberg, 1980:564].

The Delphi technique has three distinct advantages over traditional group problem-solving methods. First, experts surveyed remain anonymous. This reduces the effect of the dominant person which may sway the opinions of the other members even though the dominant view may not be correct. Second, part of the process is providing controlled feedback to the respondents concerning experts' responses from previous rounds of the technique. Again, the expert is not associated with his or her response. This controlled feedback reduces noise, defined as "...irrelevant or redundant material that obscures the directly relevant material offered by participants" (Dalkley, 1967:3). Third, in some types of surveys the Delphi technique enables the researcher to produce a statistical group response. Depending on the survey, this statistic may be the group median, mean or some other representative number, or the survey may not exact a statistical consensus at all. Calculating a group statistic is also possible witn other techniques. The advantage of Delphi is there is no pressure to conform to one opinion. A distribution of opinions about the mean, median or consensus may be just as useful to the research (Dalkley, 1967:3).

The personnel solicited were chosen because they had worked with the Panel from a variety of perspectives. This deliberate variety was an effort to include expert opinions from all levels of the work force which would be exposed to the Panel, thereby instilling additional rigor to a process which has been criticized by some as lacking rigor (Sackman, 1974:17). The engineers who developed the Panel at the US

Army Construction Engineering Research Laboratory (USA-CERL) were included in the technique. Technicians and engineers from the other Panel locations -- Grand Forks Air Force Base, ND; FE Warren Air Force Base, WY; and the University of Missouri, Columbia, MO -- were queried concerning their experiences with Panel design and installation. Additionally, Honeywell Controls and Johnson Controls companies are actually manufacturing or in the manufacturing-ready phase for the Panels. Opinions were requested from the designing engineers and technicians at each of the manufacturers. Expert opinions were also solicited from Mr Jerry Williams at HQ USAF/LEEEU, who mandated the use of the Panel, and specific technicians at the Engineering and Services Center at Tyndall Air Force Base, FL who had worked with the Panel. The first round of the technique was conducted via telephone interviews. The second round consisted of written correspondence and included a consolidation of the information gathered from the first round. The third round was also written and included a consolidation of all information gathered from round two. Questioning the experts on three separate occasions and providing them feedback was done in an effort to

> ...stimulate the experts into taking into due account considerations they might through inadvertence have neglected, and to give due weight to factors they were inclined to dismiss as unimportant on first thought [Brown, 1968:3].

The purpose of obtaining these expert opinions was to reach a consensus concerning the design, installation, reliability and diagnostic capability of the Panels, based on their experiences.

Questions used during the written portion of the technique were reviewed by mechanical engineers in the Graduate Engineering Management 89S class and three mechanical engineers who were instructors in the Air Force Institute of Technology School of Civil Engineering and Services Mechanical Engineering Section. The mechanical engineering discipline was chosen based on the reviewer's familiarity with the subject.

Hypothesis

The primary emphasis of this research was to determine if an operational difference existed between the Standard Control Panel and built-up systems. It was generally believed that the Panel would have better performance characteristics than the average built-up system. However, because of personal preferences among technicians and engineers concerning controls components, especially within controls companies, the researcher did not believe a consensus would be reached concerning the Panel's comparative worth. Additionally, since the built-up system at Building 125 was installed by a technician who was aware of the comparison, additional care, either conscious or unconscious, could be anticipated on his part. Therefore, it would be more difficult to establish a difference between the systems. So the hypothesis for the research was the following:

> The difference between the Air Force standard Control Panel and other control systems in terms of ease of design and installation, ability to control in the intended manner, and reliability as measured by drift from setpoint is not significant enough to warrant mandated use of the Panel.

The alternate hypothesis was the following:

> The difference between the Air Force standard Control Panel and other control systems in terms of ease of design and installation, ability to control in the intended manner, and reliability as measured by drift from setpoint is significant enough to warrant mandated use of the Panel.

The first two terms in the hypotheses -- ease of design and installation and ability to control in the intended manner -- are qualitative and were based on the opinions of the experts surveyed and the experiences of the researcher. The third term, comparative reliability, was measured using a more sophisticated test statistic which is described in the next section. Rejection or non-rejection of the null hypothesis was based on the results of the qualitative and quantitative portions of the experiment combined with the consensus of the majority (greater than 50%) of the experts from the Delphi survey.

Test Statistic

The comparison between the Standard Panel and the built-up system was done qualitatively and quantitatively. The qualitative analysis of the data to reject or not reject the drift portion of the null hypothesis was performed using time-series analysis or regression analysis with time as the independent variable (Kachigan, 1986:423). This analysis included, where appropriate, an extrapolation of drift rates, based on the regression line for each control system, to the point where the controller would be 10 degrees Fahrenheit out of calibration. The length of time associated with this point represents when the controller should be recalibrated. Information such as this is useful from a management perspective.

The quantitative portion used time-series combined with indicator variables (Neter and Wasserman, 1974:317). The observations (weeks) variable was X1 and the indicator variable was X2. The indicator variable was 0 if the built-up system data was used in the regression equation and 1 if the Panel data was used in the regression equation. The overall equation for which regression was fitted was the following:

$$\text{drift} = B0 + \text{time}(B1) + \text{panel}(B2) + (\text{panel}*\text{time})B3$$

For the built-up system data, the equation was the following:

$$\text{drift} = B0 + \text{time}(B1)$$

This is because, for the built-up system data, panel = 0. For the Panel system data, the equation was the following:

drift = B0 + time(B1) + (1)(B2) + (1*time)(B3) or

drift = (B0 + B2) + time(B1) + time(B3)

This is because, for the panel data, panel = 1. The additional slope, hence additional drift, was measured by the B3 value. The significance of the contribution of B3 to the model was the test statistic. In regression, the coefficients have a t-distribution. The measure of whether or not the particular coefficient could occur by chance or is significant is a t-statistic and its significance is represented by a p-value. The p-value is the probability of observing the random t-statistic greater than that obtained by the regression calculations (Kachigan, 1986: 143,257). If this p-value was less than 0.05, the decision rule was to reject the null in favor of the alternate that there is a significant difference between the two system drifts. Additionally, the added value of B2 to B0 may have increased the y-intercept of the regression equation. This was not significant since both systems were calibrated to begin with zero drift, hence a zero y-intercept.

Although the comparison included some cost factors, such as Panel cost compared to that of a built-up system, no attempts were made to justify the Panel based on the dollar amounts saved. The majority of the analysis done and the conclusions reached were based on judgement and could not be quantified in terms of dollars and cents.

Conclusion

The past three chapters discussed maintenance and maintainability -- a major problem with regard to HVAC control systems. The chapters reviewed literature on the problem, possible solutions in the controls industry and the implications for the Air Force. The literature review led the reader through the problem-solving process to the Air Force's solution. This solution was a standard control design using a Standard Panel. Prior to this research, however, the solution was untested.

To test the solution, the researcher constructed an experiment and obtained expert opinions concerning the Panel using a survey technique called the Delphi Method. The METHODOLOGY chapter outlined both of these procedures. The next chapter contains all the data collected during the procedures and its subsequent analysis. The fifth and final chapter contains the conclusions reached from the data analysis and recommendations for future research.

IV. Data Collection and Analysis

Chapter Overview

The previous three chapters described the preliminary work for this chapter. The first chapter introduced the problem -- reliability and maintainability in control systems. The second chapter analyzed and compiled other research done on various types of control systems: pneumatic, electronic, DDC, and the Air Force Standard Control Panel. The third chapter outlined the method the researcher would use to compare the Standard Panel to built-up systems. This comparison tested the hypothesis that the Standard Panel is not superior enough to the built-up systems in terms of ease and completeness of design, ease of installation, ability to control in the intended manner, and reliability and diagnostic capability to warrant mandatory use of the Panel. The method included an experiment and the Delphi technique. In this chapter, the information collected during both the experiment and the Delphi technique was presented and analyzed.

The information presented in this chapter was divided into three parts. The first part is a qualitative analysis of the installation, calibration and operations phases of the Standard Panel experiment. Any experiences the researcher believes are significant during these phases or while collecting data, particularly in comparison with the built-up system, are mentioned.

The second part is a qualitative and quantitative analysis of the drift from setpoint of the system caused by both the Standard Panel and the built-up system components. Comparisons are only made between the mixed air and cooling coil components of each system. The qualitative portion describes the comparative rates of drift of each system. The quantitative part determines if one rate of drift is significantly greater than the other.

The third part of this chapter includes an analysis of the responses from the experts as solicited by the Delphi process. Both the information where the experts agreed and where they disagreed are presented.

Installation, Calibration, and Operation

Installation. During the installation phase, the Panel, sensors, and actuator feedback position potentiometers were mounted. Additionally, the wires and pneumatic tubing were run and connections were made from the Panel to the appropriate hardware. This process began on 1 Aug 88 and lasted the entire month, taking approximately 8 hours to install the Panel, 12 hours to install the sensors, and 16 hours to fabricate and install the potentiometers. No major problems were encountered. However, the significant events are described in the next few paragraphs.

Due to the size and weight of the Panel, two-by-fours were required on both sides of the non-load-bearing wall to support the Panel. Although the Panel is quite heavy, this portion of the work was done by the researcher alone. Four-wire shielded cable as required by the manufacturer's instructions (Chostner, 1985) was not available on Wright-Patterson AFB. The researcher used 4- and 5-wire twisted cable as a substitute and found no erratic readings as a result of the substitution.

While installing the actuator position potentiometers, the researcher discovered the outside air actuator did not move the dampers. Attempts to solve the problem by tightening the bolt at the actuator-damper connection resulted only in the actuator not moving at all, which indicated the damper was frozen shut. After removing the damper hood, the researcher discovered that a screw held the damper louvers shut. The screw was removed, thus enabling the actuator-damper system to function.

This situation is recorded here not only because it indicates a problem in the existing system, but also because it is a good example of the ease with which the condition of the HVAC system can be diagnosed via the Panel. The frozen damper was not detected by reading gauges on the built-up system. To do so would have required knowledge of the control system design, including throttling ranges or proportional bands, and sensor ranges. It would have also required some means of manually controlling the pressure to the actuator. On the other hand, detecting the problem via the Panel required only that the researcher manually adjust the pressure to the actuator (a process for which the Panel operator simply pushes the "set" button and turns a knob to adjust the pressure, a feature not included in the built-up system), and monitor the temperature in the mixed air section by observing the readout at the Panel.

During installation, all wires and tubing sections were labelled. The connection points on the Panel to which the wires and tubing should be connected were not labelled by the manufacturer, so some trial and error was required to ensure the connections were correct. The researcher recommends that these labels be included in the specifications to the various Panel manufacturers.

Calibration. Of the three phases -- installation, calibration, and operations -- the researcher had the greatest difficulty with calibration of the Standard Panel. This was due primarily not to any deficiency in the Panel itself but to the lack of positive positioners on the actuators. Positive positioners serve to regulate the air pressure to the actuator so the motion of the actuator is proportional over a certain range to the air pressure. For the Standard Panel, the pressure should have been 3.5-14.5 psi to move the actuator from zero to 100 percent open.

The analysis of the calibration problems which follows will begin with the calibration of the return air and outside air position potentiometers. Next, the researcher determined the opening and closing ranges of the return air, outside air, and exhaust air dampers. The researcher then determined the relationship between meter readings for the return air and outside air and the actual percentage of return air and outside air flowing through the mixed air section. The presented information will also include the calibration of the sensors, the pneumatic to electronic switches, the controllers, and the air pressure gauge which was used to measure air pressures on the built-up system throughout the experimental period.

First, the position potentiometers were calibrated. During this process, it was determined that the resistance originally installed in the potentiometers was not large enough. The researcher knew that a span of at least 60 ohms was required over a range of motion of approximately 60 degrees. Therefore, a 350 ohm resistor was originally used. When an insufficient change in the resistance caused the meter range to be less than 100%, the 350 ohm resistor was replaced with a 500 ohm resistor. There was some difficulty concluding that the source of the problem was the resistor size since both gain and zeroing are required on the Panel to calibrate the damper position indicators. However, the ability to control the pressure via the Panel made the job much easier than performing the task without this feature. Both meters were then calibrated using the zero and gain on the Panel and functioned thereafter with no problems.

Next, the researcher manually adjusted the pressure to the return air, outside air, and exhaust air dampers, watched them open and close, and noted the pressures at which each began to open and finally close. These pressures are shown on the following table.

Table 1. Opening and Closing Pressures for Return Air, Outside Air and Exhaust Air Dampers

	Pressure Increasing		Pressure Decreasing	
	Open	Closed	Closed	Open
Return Air with pos. indicator	7	9.5	9.0	6.5
Return Air w/o pos. indicator	8	11	11.0	7.5
Exhaust Air	6.5	13	11.0	5.5
	Closed	Open	Open	Closed
Outside Air	7.5	11.5	11.0	7.5

As can be seen in the above table, the operating range for the actuators was much narrower than the recommended 3.5-14.5 psi. Additionally, significant differences exist between the opening and closing ranges as the pressure increases from 4.0 psi compared to the ranges as pressure decreases from 15 psi. This is called hysteresis.

The researcher also calibrated the open percentages for the mixed air and return air dampers. The percentages on the meters for each damper are strictly linear based on increased resistance through the potentiometer. But since there were two return air dampers each with individual opening and closing ranges but only one return air meter on the Panel, a relationship had to be established between the readings on the meters and the actual percentage of return and outside air which combines in the mixed air section of the HVAC system. This was done using the following equation:

$$\text{mixed air temp} = (F)OA + (1-F)RA$$

where F = the specified outdoor air fraction

OA = outdoor air temperature

RA = return air temperature [USAF, March 1987;33]

To determine the fraction of outdoor air from this equation, simple algebraic maneuvers are performed to yield the following:

$$F = (MA-RA)/(OA-RA)$$

The data used is shown in Tables 2 and 3 and Figures 9, 10, 11, and 12. Using the relationship determined in this process, minimum outside air was set at 20%.

Table 2. Air versus Dial Settings 100%-0%.

Outside Air Meter %	Return Air Meter %	Actual Outside Air %	Actual Return Air %
100	0	98.4	1.6
100	0	98.3	1.7
100	0	97.9	2.1
100	0	97.4	2.6
100	0	98.0	2.0
100	0	99.0	1.0
100	0	97.2	2.8
100	0	95.7	4.3
100	0	97.3	2.7
100	0	100.0	0.0
100	0	97.3	2.7
100	0	97.2	2.8
100	0	88.5	11.5
100	0	80.8	19.2
100	0	76.3	23.7
100	0	68.9	31.1
90	2	57.5	42.5
80	12	48.1	51.9
70	22	43.0	57.0
60	34	35.6	64.4
50	46	28.2	71.8
40	58	22.6	77.4
28	74	18.3	81.7
18	86	15.8	84.2
14	94	14.5	85.5
12	94	13.9	86.1
2	96	11.1	88.9
0	96	11.0	89.0
0	96	10.3	89.7
0	96	10.9	89.1
0	96	10.8	89.2
0	96	12.7	87.3
0	96	11.2	88.8
0	98	12.1	87.9
0	98	17.0	83.0
0	98	18.2	81.8
0	98	19.6	80.4
0	98	17.7	82.3

Table 3. Air versus Dial Settings 0%-100%.

Outside Air Meter %	Return Air Meter %	Actual Outside Air %	Actual Return Air %
0	98	7.8	92.2
0	98	7.4	92.6
0	98	10.0	90.0
0	98	7.5	92.5
0	98	10.4	89.6
0	98	9.1	90.1
0	98	12.0	88.0
0	98	11.9	88.1
0	96	11.1	88.9
0	96	10.3	89.7
0	96	11.1	88.9
0	96	11.1	88.9
0	96	10.6	89.4
0	96	9.5	90.5
0	96	12.2	87.8
0	96	11.9	88.1
0	94	9.8	90.2
0	94	11.8	88.2
0	60	10.9	89.1
2	52	12.0	88.0
2	42	12.0	88.0
2	32	14.2	85.8
4	20	16.9	83.1
8	8	16.7	83.3
86	0	57.7	42.3
100	0	66.4	33.6
100	0	76.8	23.2
100	0	84.8	15.2
100	0	94.1	5.9
100	0	99.4	0.6
100	0	100.0	0.0
100	0	100.0	0.0
100	0	100.0	0.0
100	0	100.0	0.0
100	0	100.0	0.0
100	0	99.5	0.5
100	0	100.0	0.0
100	0	100.0	0.0
100	0	100.0	0.0
100	0	100.0	0.0

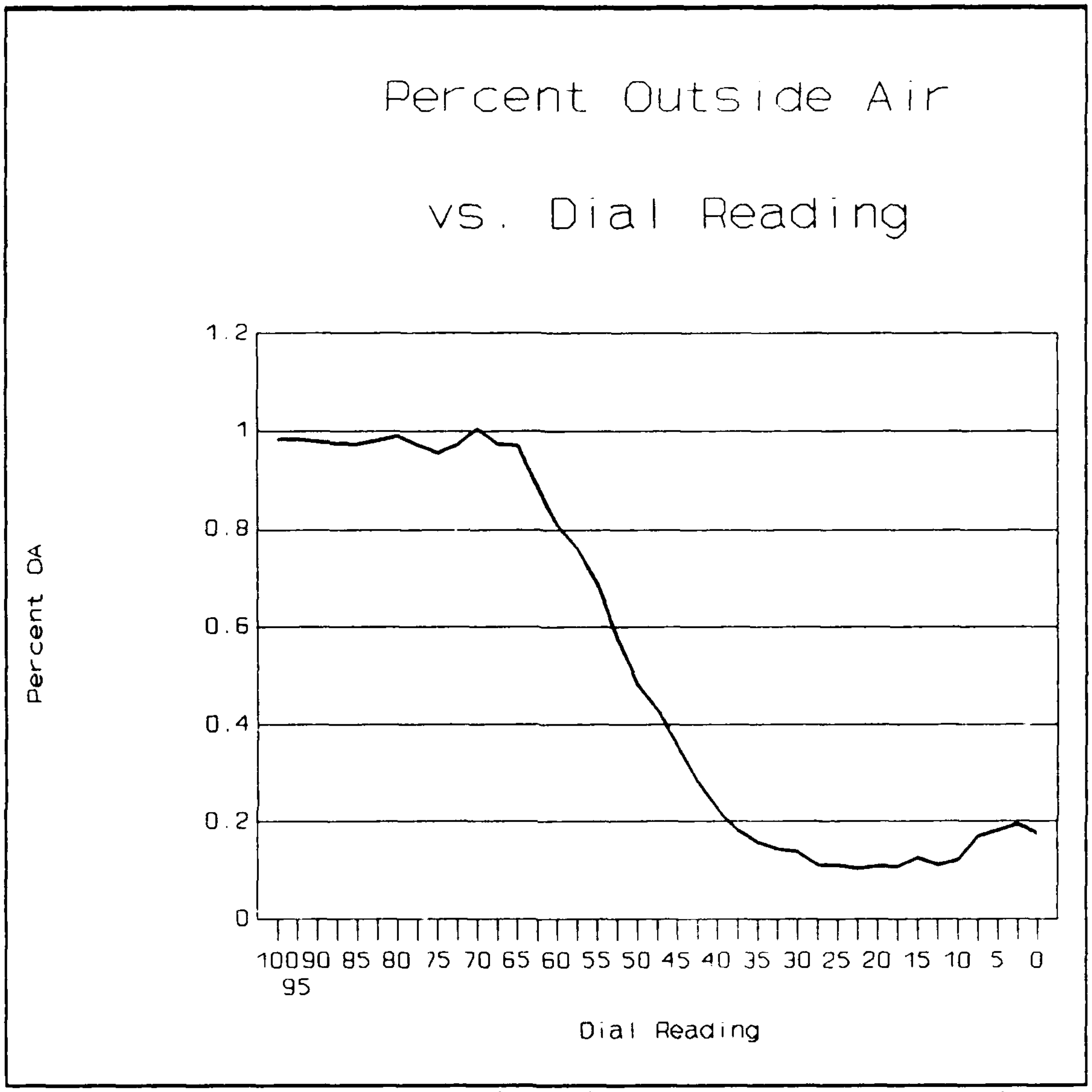


Figure 9. Percent Outside Air (Decreasing Pressure)

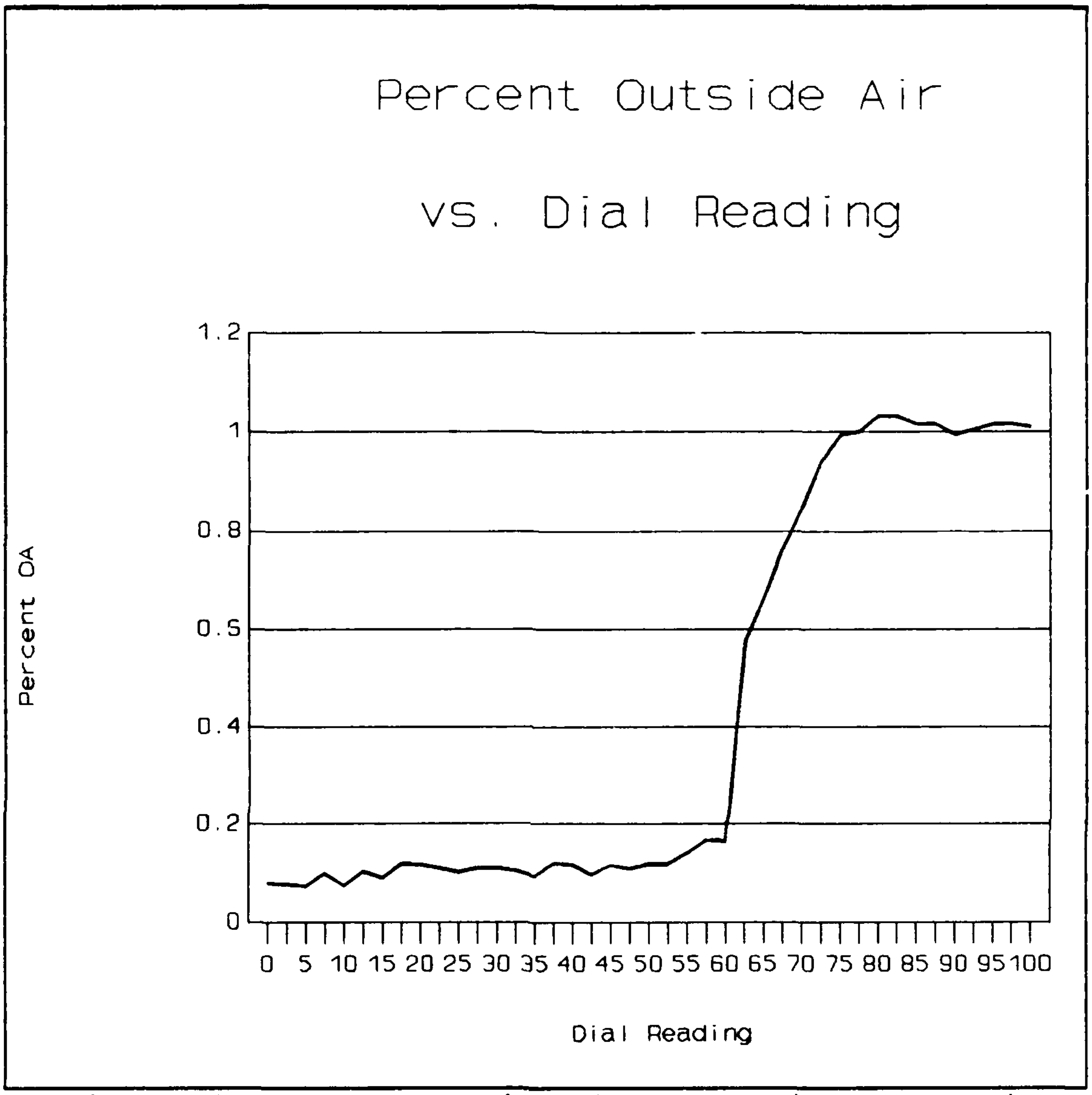


Figure 10. Percent Outside Air (Increasing Pressure)

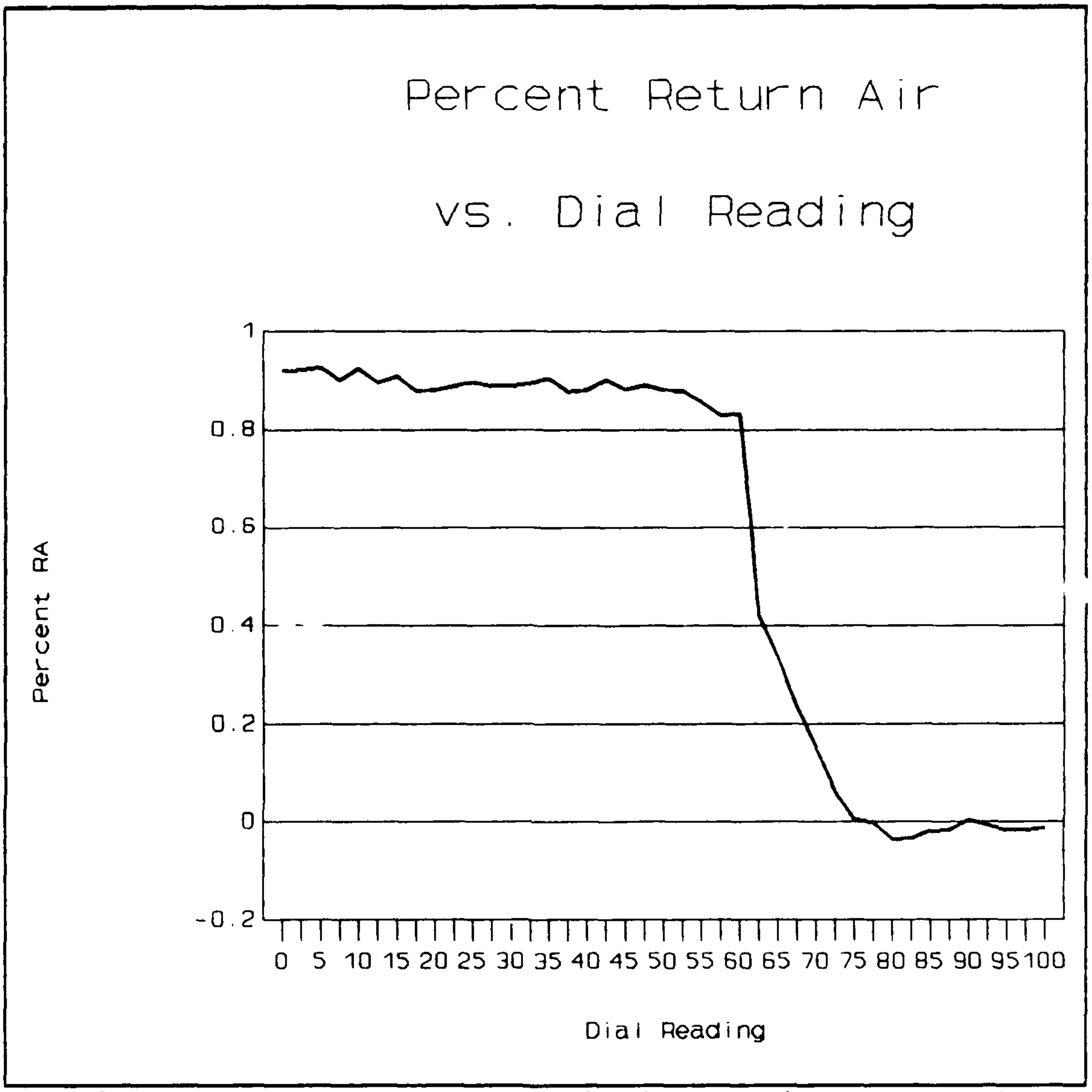


Figure 11. Percent Return Air (Increasing Pressure)

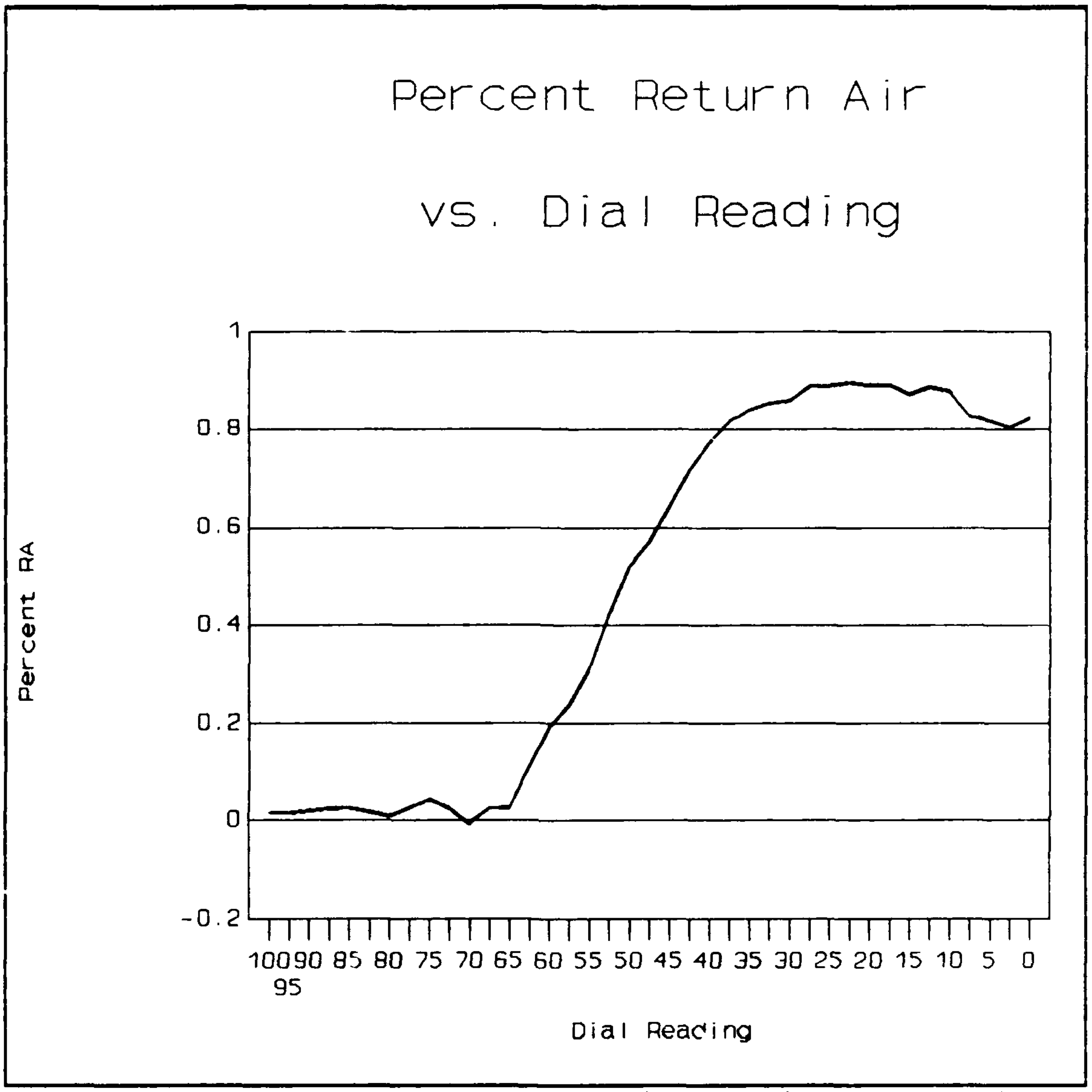


Figure 12. Percent Return Air (Decreasing Pressure)

Thirdly, all sensors were tested for accuracy, first using a recently calibrated Fluke 77/AN multimeter with a 80TK thermocouple module borrowed from the Civil Engineering Control Shop. In addition to comparing the temperature readout from the Panel with the multimeter, resistance was measured by the multimeter across four Panel terminals for each sensor, averaged, and from this, the sensor temperature was calculated using the transformation formula 100+/-0.385ohms per degree Celsius at 0 degrees Celsius. This dual recording system was used to ensure no errors existed within the Panel's resistance-to-temperature conversion capability. The data collected during these sensors tests are presented in Table 4:

Table 4. Sensor Calibration Test-I.

Terminal Colors	Measured Resist	Degrees	Panel Reading	Shop Meter
SUPPLY AIR				
White Yellow	105.3Ohms	13.8oC	55.5oF/13.1oC	59.5oF/15.3oC
White Red	104.9Ohms	12.7oC		
Black Red	104.9Ohms	12.7oC		
Black Yellow	105.3Ohms	13.8oC		
Average	105.1Ohms	13.2oC		
		55.8oF		
MIXED AIR				
White Yellow	108.5Ohms	22.1oC	69.7oF/20.9oC	73.4oF/23.0oC
White Red	108.4Ohms	21.8oC		
Black Yellow	108.6Ohms	22.3oC		
Black Red	108.6Ohms	22.3oC		
Average	108.5Ohms	22.1oC		
		71.8oF		
OUTSIDE AIR				
White Yellow	109.9Ohms	25.7oC	69.4oF/20.8oC	73.4oF/23.0oC
Black Red	108.9Ohms	23.1oC		
Black Yellow	108.8Ohms	22.9oC		
White Red	109.9Ohms	25.7oC		
Average	109.4Ohms	24.4oC		
		75.9oF		
RETURN AIR				
White Green	109.2Ohms	23.9oC	69.0oF/20.6oC	73.0oF/22.8oC
Black Green	109.2Ohms	23.9oC		
White Red	109.2Ohms	23.9oC		
Black Red	109.2Ohms	23.9oC		
Average	109.2Ohms	23.9oC		
		75.0oF		

Notes:
1. Wire colors are those coming from the respective sensors.
2. Temperature from measured resistance based on the following equation:

Temp(oC) = (Resistance - 100)/(0.385ohms per oC)

3. Panel reading is temperature as read from the Panel meter.
4. Shop meter is temperature as read from Fluke multimeter.

The data collected indicated all four sensors, as measured by the Panel meter, were approximately 4oF below the Fluke multimeter readings. The data also indicated a 0.3oF to 6.5oF difference existed between the temperatures as read from the Panel meter compared to those calculated from the resistance measurements. To isolate the cause of these discrepancies, another multimeter was obtained and the procedure duplicated. The second multimeter was a 8022B Fluke multimeter with an 80T-150U Fluke temperature probe borrowed from the Mechanical Engineering Faculty of the School of Civil Engineering and Services. Since the purpose of this second test was to detect a difference between the Panel readings and the multimeter readings, not to detect an error within the Panel, no data were collected from the terminal connections. Temperature readings were only made at each sensor location with the multimeter and compared with the readings from the Panel meter. The data from this test are presented in Table 5 as follows.

Table 5. Sensor Calibration Test-II.

	Panel Reading	Multimeter Reading
	(Degrees Fahrenheit)	
Supply Air	79.3	78.9
Mixed Air	77.2	76.6
Outside Air	70.4	69.9
Return Air	78.5	78.0

These data indicate the sensor temperatures, as read by the Panel meter, are accurate to within 0.7 degrees as compared with the calibrated multimeter, which is adequate for this experiment. Because no significant discrepancy was found during this second test, no subsequent tests were performed to compare temperatures calculated from the terminal resistances with meter readings. During the test procedure, one problem was noted by the researcher. Because there were no ports in the air ducts to insert the temperature probe, it had to be inserted at the sensor location, thereby requiring the removal of the sensors. This is an unnecessary inconvenience which can easily be solved in most HVAC applications by requiring the contractor to construct ports in the duct for such purposes.

To ensure the electronic sensors used by the Panel did not drift during the time the data was collected (November 1988 through May 1989), the sensors were again checked using a recently calibrated Fluke 8022A multimeter with a Fluke 80T-150U temperature probe borrowed from the Mechanical Engineering Faculty of the School of Civil Engineering and Services. The data collected from this comparison are presented in Table 6 as follows.

Table 6. Sensor Calibration Test-III.

	Panel Reading	Multimeter Reading
	(Degrees Fahrenheit)	
Supply Air	52.8	53.1
Mixed Air	72.6	72.2
Outside Air	76.8	77.2
Return Air	71.0	71.0

These data indicate the sensors' temperatures as measured by the Panel meter remained within 0.4oF of temperatures measured by a calibrated multimeter.

It was also determined that the Standard Panel could not control the pneumatic-to-electronic relays which energized the cooling coil solenoid valves due to the operational sequence of the built-up system. The setup of the relays was as follows:

	ON (psig)	DIFFERENTIAL (psi)
RELAY 1	5.0	3.0
RELAY 2	7.0	3.0

This meant that the pressure from the Panel had to drop as low as 2 psi to turn off the relay controlling coil #1. However, the pressure range from the Panel was only 4-14 psi. Therefore, a 2 psi air reducing restrictor was installed in the Panel pressure output line to enable Panel control. The new control pressures from the Panel were the following:

	ON (psig)	DIFFERENTIAL (psi)
RELAY 1	7.0	4.0
RELAY 2	11.0	5.5

Once the sensors and the potentiometers were calibrated, the calibration of the controllers began. Although attempts were made to calibrate the supply air controller, the HVAC refrigeration compressor would not function properly so the process was not completed. The problem was the compressor would frequently stop running due to low pressure. This problem was identified to the Refrigeration Shop of the Civil Engineering Squadron. However, due to the lateness in the year and the time required for a solution to be found, the problem was not fixed. Therefore, the controller was set with proportional only control and a throttling range of 10 degrees.

Calibration of the mixed air controller was very difficult due to the lack of positive positioners on the damper actuators. Without these positioners, the cycle is created on which small changes in control air pressure cause the actuator and damper to move a great deal, thereby causing a large shift of mixed air temperature. This temperature shift in the mixed air causes another overreaction in the controller, causing another temperature shift, and so on. When this situation does not stabilize, it is termed "out of control" or "hunting."

The mixed air controller calibration began with the recommendations from the manufacturer -- setting the throttling range (TR) to 10 degrees and the reset time (Tn) to 60 seconds. Throughout the calibration, the term throttling range (TR), or the range in degrees over which the controller output varies from minimum to maximum, was the same as proportional band (PB). Although the two terms are not normally congruent, the manufacturer's instructions refer to proportional band while defining throttling range. This research was congruent with the instructions. Reset time (Tn) is

> ...the time interval over which the part of the controller output signal due to the integral action increases by an amount equal to the part of the output signal due to the proportional action, when the deviation between setpoint and process is unchanging [Schwenk, 1988:3].

This setting (TR = 10, Tn = 60) required 15 minutes to stabilize -- longer than specified by the manufacturer's performance standards -- and many other combinations were tried before the final setting was determined. According to the performance standards, the settling time should be approximately 2-3 minutes (see Appendix A). This was never obtained, even by the final settings. The first set of combinations ranged from a proportional band (PB) of 10 to a PB of 100 and an integral reset time (Tn) from 30-100. When no combination provided the proper performance characteristics, the researcher resorted to the Standardized HVAC Specifications which are the following:

CONTROLLER CALIBRATION INSTRUCTIONS

PROCESS REACTION CURVE METHOD

A. Assure system is on and running

B. Set all other system controllers to manual control (or adjust setpoints to provide constant output)

C. Turn integral reset Tn to highest setting (off)

D. Set proportional band setting to highest setting

E. Adjust the setpoint of the controller to introduce a system change (but remain in a range that will not cause the controller output to constantly stay at min or max value).

F. Observe response of the controller output for several minutes:

1) If the oscillation dies out to a relatively steady controller output..., then reduce the proportional band setting and go back to step E above.

2) If the controller output continues to oscillate indefinitely..., continue on to the steps below.

G. Determine, as closely as possible (Xp'), the proportional band setting (Xp') at which controller output just begins oscillation.

H. Record the time (in seconds) between the peaks in the controller output oscillation to determine the period of oscillation (Tn'), which is the period of time the process takes to repeat a cycle (i.e. the time from one peak of the oscillation to the next)....

I. Calculate Parameters:
Once the period of oscillation (Tn') has been found and Xp' has been recorded from the controller setting, the controller settings must be calculated:

[1] $Xp = 2.22 * Xp'$

[2] $Tn = .8Tn'$

J. Set Controller:
The parameters calculated in equations 1 and 2 should now be set on the controller. To test stability,

> change the setpoint to force the controller to change its output. The process variable (ex. supply air temp for the chilled water controller or mixed air temp for the economizer controller) should settle down near the setpoint within a few periods of Tn. If oscillation continues, try increasing the proportional band a small amount. If a large change is necessary, the calibration should be started over again from step A [USAF, March 1987;58.59].

When these instructions were followed, the mixed air controller became unstable at PB = 5 and the high temperature to low temperature cycle was 125-130 seconds (see Table 7, Figure 13). The cycle was multiplied by 0.8, which yielded approximately 70 seconds. Then the PB was multiplied by 2.2, which was between 10 and 15. (The dials on the gauge do not permit accuracy to less than increments of 5.) The researcher chose 15 for the PB. This combination took more than 3 Tn periods to settle down (see Table 8, Figure 14) to setpoint as well, which still exceeded the manufacturer's guidelines, so other combinations were tried.

After more than 30 hours were spent trying various combinations, the best setting was reached at PB = 15 and Tn = 80, which appeared to settle out within 5 minutes. The data in Tables 17 through 34 and Figures 21 through 38 show the system response to varying PB and Tn settings (see Appendix B).

Table 7. Mixed Air Calibration.
(Setpoint = 70, PB = 5, Tn is off)

Time (minutes)	Vout (% voltage)	MA Temp (oF)
0.0	23.1	67.6
0.5	65.0	70.7
1.0	23.1	67.8
1.5	23.1	68.6
2.0	62.0	70.5
2.5	23.1	68.0
3.0	28.0	69.0
3.5	61.7	70.5
4.0	23.5	68.1
4.5	25.0	69.0
5.0	62.6	70.5
5.5	23.1	68.1
6.0	28.0	68.9
6.5	62.0	70.4

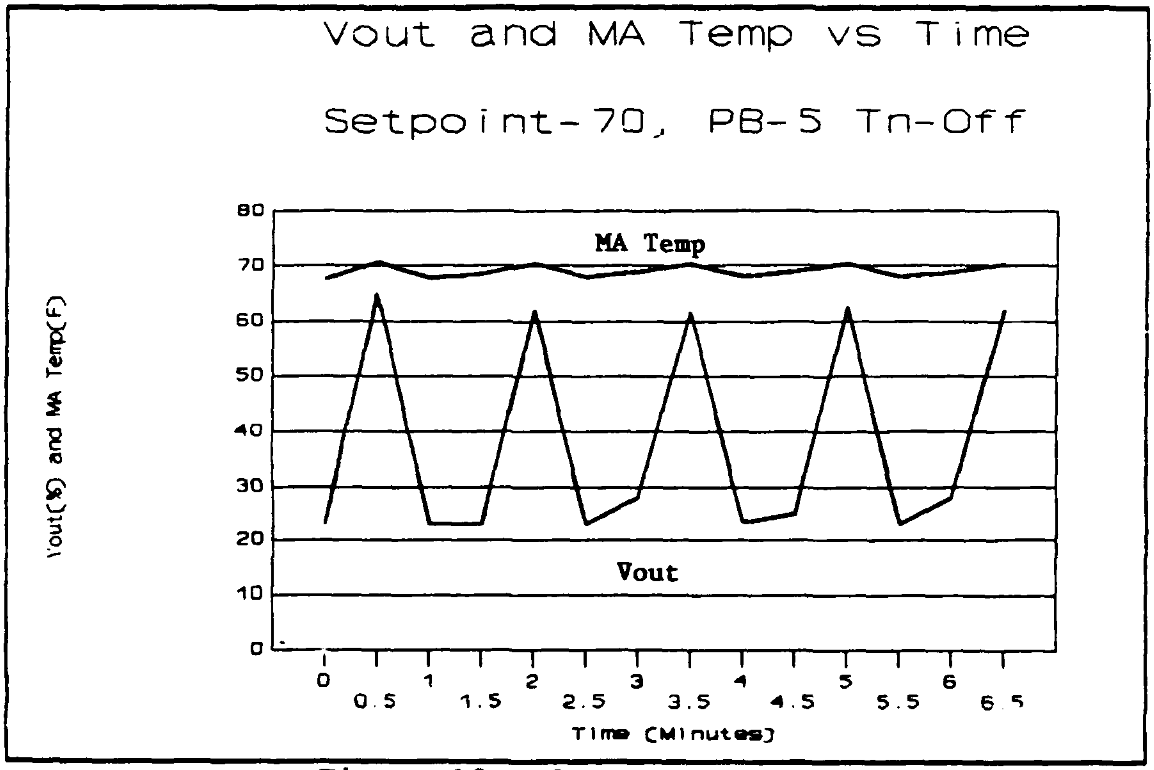


Figure 13. System Response
(Setpoint = 70, PB = 5, Tn is off)

Table 8. Mixed Air Calibration.
(Setpoint = 66, PB = 15, Tn = 70)

Time (minutes)	Vout (% voltage)	MA Temp (oF)
0.0	69.2	67.3
0.5	49.0	64.0
1.0	27.0	63.7
1.5	43.0	66.8
2.0	71.0	67.9
2.5	72.0	65.8
3.0	59.0	64.4
3.5	39.0	63.6
4.0	32.6	64.8
4.5	51.0	66.7
5.0	64.0	66.1
5.5	55.0	64.8
6.0	42.5	64.2
6.5	36.9	64.8
7.0	50.0	66.0
7.5	59.0	66.3
8.0	55.0	65.2
8.5	44.0	64.5
9.0	38.8	64.9
9.5	51.0	65.3
10.0	62.0	66.4
10.5	55.0	65.1
11.0	43.0	64.4
11.5	38.8	64.9

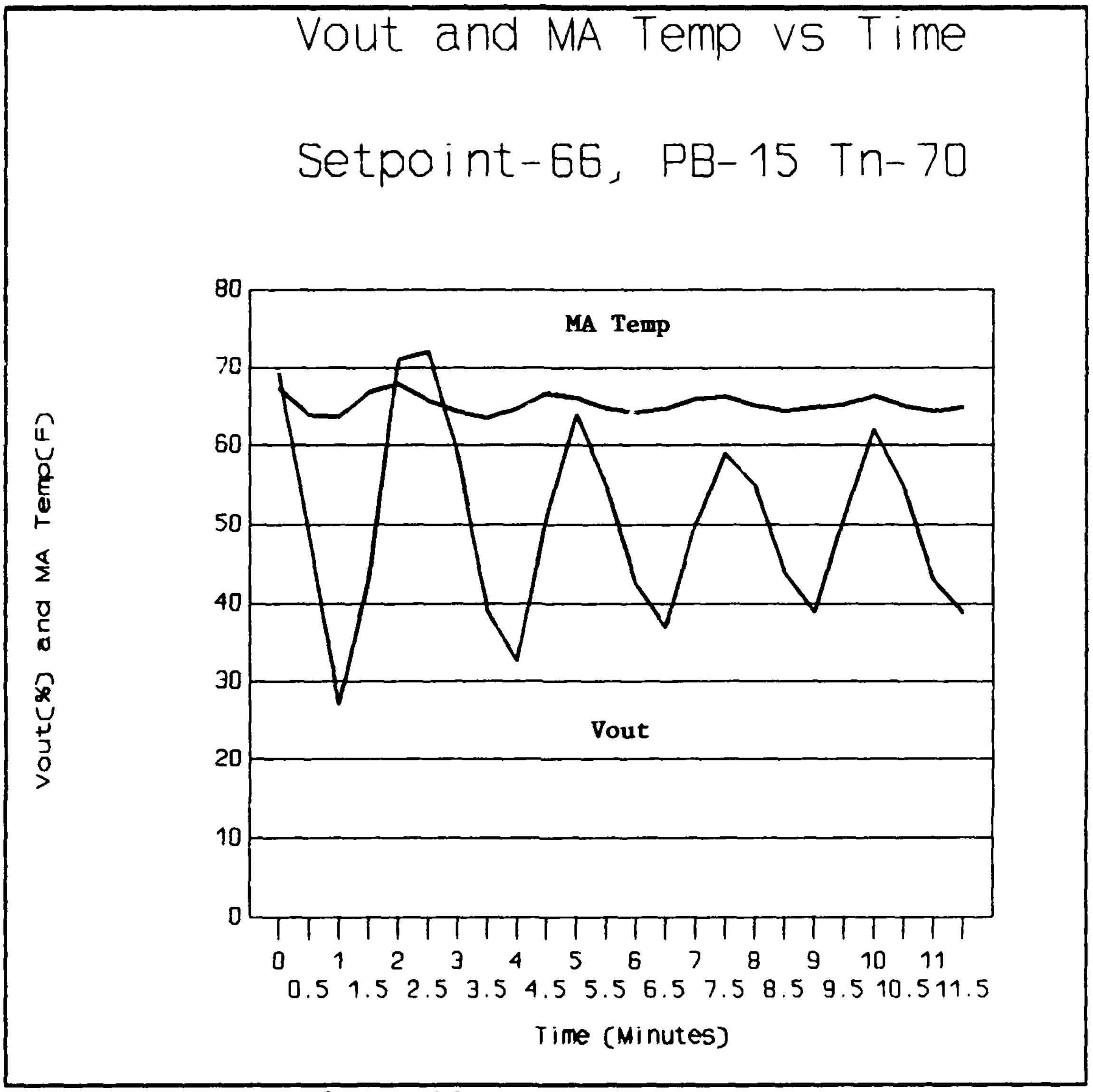


Figure 14. System Response (Setpoint = 66, PB = 15, Tn = 70)

Selecting these optimal values (PB = 15, Tn = 80) did not solve the entire problem, however. This became evident the first time the Panel operated the system all night. Because the air handler was shut off by the time clock from 1800 to 0500, the initial mixed air temperature at 0600 was approximately $20^{\circ}F$ above setpoint. A step input of this magnitude forced the controller out of control again. The researcher tried to shut off the power to the Panel to eliminate any gain caused by the integral part of the proportional-plus-integral (PI) control, but this action did not solve the problem. Even when the researcher attempted to assist the system by bringing the mixed air temperature within the throttling range of the mixed air controller or even closer -- within the range of the springs of the actuators -- the problem was not solved.

Since the MA controller did not settle satisfactorily when given an input far outside its throttling range, the researcher resorted to trial and error to find new operating settings. The Tn remained at 80 and the PB was first set to 25 degrees, then 20 degrees. In both cases, the controller settled out within 10 minutes. However, a few mornings later, the controller was given a larger step input after which it did not settle. Believing that the spring range of only 4 psi instead of 11 psi may indicate some expected proportionality in terms of the proportional band, the researcher then adjusted the PB 2.5 times higher to 50 degrees. Still, the problem was not eliminated.

After another 35 hours of trial and error, the researcher settled on a PB = 35 and Tn = 150. Since the calibration changes were made one day and the system was checked for stability the following day, no data for tables or graphs were recorded for this portion of the calibration. Such data collection would have required 24-hour observation. The PB = 35 and Tn = 150 setting worked through the end of the research period. Although the solution was eventually found, the researcher's inability to quickly solve the calibration problem caused a one-month delay in collecting data.

The most recent problem resulting from the lack of positive positioners occurred when the freezestat was tripped upon switching control over to the Standard Panel from the built-up system. During a period of two weeks in February 1989, when the outdoor air temperature was less than 20°F, whenever the researcher attempted to allow the Standard Panel to control the system, the outdoor air dampers would immediately open 100% responding to the high mixed air temperature under built-up system control. Then, because the pressure would continue to drop down to 3.5 psi, well past the 100% open pressure of about 7 psi, too much cold air would enter the mixed air section and trip the freezestat. As with the other problems, this may be solved in other HVAC applications by installing positive positioners.

When calibrating the controllers, the integral part of the proportional and integral control was not enabled on the supply air controller which controlled the cooling coils. This was because the two-stage direct expansion system can not provide exact temperature control of the supply air. Temperatures within the 10 degree throttling range would only result in either one or both of the stages engaging. PI control would force the coils to cycle on and off, possibly causing damage to the system without more accurate control.

Proportional-plus-integral control was enabled on the mixed air controller because exact temperatures could be obtained in the mixed air region from the mixture of outside and return air when the dampers were properly operating. The mixed air controller regulated the dampers only when permitted by the economizer, a device which compares outside air to return air. The economizer is a logic device which, when the outside air temperature is 1.8oF below the return air temperature, determines it would be of economic benefit to use the outside air to cool the mixed air. When the outside air warms to 1.8oF above the return air, the economizer disengages and does not permit the mixed air controller to control the dampers. Then, only minimum outside air is allowed into the system.

Because of the economizer settings (which could not be adjusted), a problem emerged. When outside air was cool enough to enable mixed air control but was very humid, the cooling coils could not cool the supply air as much as if the mixed air consisted of only minimum outside air. An example of this was on 10 September 1988 when the supply air temperature with 100% return air was 57oF compared to 65oF when the mixed air controller allowed 100% outside air. This additional heat content in the air from the humidity blown into the space caused the return air temperature to rise as the outside air temperature was also rising. Both temperatures continued to rise, creating uncomfortable conditions in the space until the outside air temperature finally rose fast enough for the economizer to disengage the mixed air controller.

To avoid creating uncomfortable conditions such as the ones described in the example, a better system of temperature comparison would have been to create the logic in the economizer which compares temperatures of return air minus 5 or 10 degrees Fahrenheit and shut off when the outside air temperature is 2oF below return air. This logic avoids blowing warm, humid air into the space and reduces the load on the cooling system.

Lastly, the researcher calibrated a gauge used to take measurements on the built-up system. This calibration was done using a digital adjustable pressure gauge. It was determined that the pressure gauge used for the built-up system was 1/2 psi high. This was the most accurate of all gauges tested and was consistent. The measurements taken are shown on the following page.

Table 9. Pressure Gauge Calibration

Digital Pressure Gauge Reading (PSI)	Honeywell Gauge Reading (PSI)
.5	0.0
1.0	1.5
1.5	2.0
2.0	2.0
2.5	3.0
3.0	3.5
3.5	4.0
4.0	4.5
4.5	5.0
5.0	5.5
5.5	6.0
6.0	6.5
6.5	7.0
7.0	7.5
7.5	8.0
8.0	8.5
8.5	9.0
9.0	9.5
9.5	10.0
10.0	10.5
10.5	11.0
11.0	11.5
11.5	12.0
12.0	12.5
12.5	13.0
13.0	13.5
13.5	14.0
14.0	14.5
14.5	15.0
15.0	15.5
15.5	16.0
16.0	16.0
16.5	17.0
17.0	17.5
17.5	18.0
17.8	18.0

Note: This gauge was also compared on a weekly basis to the mixed air gauge in the Standard Panel to ensure no major differences existed.
Digital Pressure Gauge was a Setra, S/N 80124, Model 360, 0-20psi, 117VAC, 60Hz.

Operation. During operation of the research system, the differences between the control schemes of the built-up and Panel systems, the relative costs, and the diagnostic capabilities were of particular importance. First, the researcher notes a difference between the supply and mixed air control strategies used by each system (see Appendices A and C). The logic from the built-up system did not permit cooling of the supply air to occur when the outside air temperature was below 60°F. This logic normally ensures the space does not become uncomfortably cool. On the other hand, the Standard Panel had instructions to provide 55°F supply air regardless of the outside air temperature or space temperature. The Panel control scheme assumed the VAV controllers would restrict the air flow enough and the perimeter heaters would be at the correct temperature to maintain a comfortable temperature in the space.

Each logic has its good and bad points. When the built-up system was controlling and the space was too warm, approximately 78°F for example, and the outside air was 58°F, the supply air was about 62°F, which did not provide sufficient cooling. The severity of the problem could have been reduced by lowering the mixed-air control temperature to 55°F as opposed to the existing 60°F setting.

On the other hand, when the Standard Panel was controlling to provide 55°F supply air and 52°F mixed air regardless of the space temperature, the return air temperature occasionally fell to 67oF (see Table 15). This occurred before the VAV boxes were calibrated by the CE Controls Shop and before steam was available for the perimeter heating system. After the heating system was functioning and the VAV boxes were calibrated, return air temperatures ranged from 68-72oF as the perimeter heat responded to the 55oF supply air and the outside air temperatures. Return air temperatures of 68-72oF indicate the system was functioning properly.

The built-up system did not control mixed air in the same manner the Panel did either. The built-up system was centered around a switch which received a signal from the return air sensor. The throttling range on the switch was very wide -- approximately 25 degrees -- so the return air had to be hotter than 82oF before the switch would activate and enable the mixed air controller to work (see Table 16). In fact, the researcher observed mixed-air control on only one occasion between January and March 1989 in spite of the numerous occasions when the return air temperatures were above the normal comfort level of approximately 75oF. This method was an advantage in the winter because the load on the heating system was not as great as when the Panel provided 55oF supply air. However, since the built-up system did not provide any mechanism for minimum outside air, hot stuffy conditions frequently resulted.

The relative costs of each system are significant. The built-up system cost approximately $750 in parts (all rebuilt) and 100 hours in labor to install and calibrate, excluding rebuild time for which data was not available. It controlled mixed air, static pressure, hot water for the heating system and supply air temperature. The Panel used in this experiment cost approximately $10,920 and took roughly 160 hours to install including calibration time. It controlled only mixed air and supply air temperatures. If Standard Panels were used, the cost for controlling the same actions as the built-up system would be approximately $30,000 in parts alone.

Controlling temperatures is not the only purpose of a control system, however. In terms of ease of understanding the HVAC system performance via the gauges and diagnosing problems with the system, the Panel far exceeded the built-up system. Although the built-up system had air ports to attach an air pressure gauge, this operation was time-consuming in that the act of attaching the gauge to the sensor port destabilized the controller. The researcher was then required to wait until stabilization was achieved, take the reading, and remove the gauge, thereby destabilizing the controller again. This procedure generally took about 30 minutes for each set of measurements excluding conversion time to change the air pressure readings into proper temperature units.

Comparing this with the features of the Panel one can readily see an advantage. Using the air pressure gauges and digital temperature indicator on the Panel, readings took less than five minutes and were already converted to familiar units. Additionally, the reader is reminded of the instance mentioned earlier during which the diagnostics of the Panel were used to find the screw in the outside air damper.

On another occasion, the Panel was used to ascertain a problem which was not discovered during installation of the built-up system. This problem was alluded to in the calibration discussion. On 8 September 1988 the Standard Panel controlled the HVAC system for the first time. Using the Panel diagnostics (supply air = mixed air plus heat gain from fan), it was determined that the cooling coils were not functioning because the compressor was off. The HVAC system was reset and functioned until the compressor stopped due to low pressure again. (The same problem discussed earlier which was identified to Civil Engineering.) This instance is mentioned again because it is another example of the ease with which diagnostics can be performed through the Panel. To determine the cooling coils were not functioning, all that was required was to turn the knob controlling the pneumatic-to-electric switches for the solenoid valves and look at the temperatures of the air before and after passing by the cooling coils.

Drift Analysis

The methodology chapter outlined the construction of an experiment to test the drift incurred by the mixed air and supply air controllers of the Standard Panel against a typical built-up system. The chapter also discussed the method of data analysis, which is regression of the drift variable versus time. This section will present the data and its subsequent analysis.

The data collected on the built-up system included the following items: date of collection, input (shown as I or 1,2 on the various controllers) and output (shown as B) pressures for the mixed-air (MA), changeover, static pressure, hot water converter, and discharge air (or supply air, SA) controllers. Additionally, outside air (OA), return air (RA), mixed air (MA) and supply air (SA) temperatures, and MA and SA setpoints, output voltages and pressures for the Standard Panel were recorded. This data was collected for a period of 29 weeks and can be seen in Tables 10-16. Also included in these tables are the absolute values of the calculated differences between the actual values produced by the controller and the output values for a controller if it were in calibration for a specified input temperature. It is the absolute value of these differences, or the drift, on which this study will focus its attention. The input temperatures for the built-up system were measured by 1) the built-up system and 2) the

Panel. Additional notes are provided on the data charts themselves.

Table 10. Data for

Built-up System Mixed Air Controller

(Setpoint = 55oF, PB = 10, TR = 10oF)

Week (Date)	Input Gauge (PSI)	Input Temp (F)	Input Panel (F)	Output Gauge (PSI)	Output Calib Gauge /Panel	Calib-Actual Gauge /Panel
1 (7 Nov 88)	9.5	54.2	56.8	9.0	7.2/9.8	1.8/0.8
2 (14 Nov 88)	9.5	55.6	54.2	7.5	8.6/7.2	0.6/0.8
3 (21 Nov 88)	8.5	55.0	45.8	8.5	8.0/3.0	0.5/5.5
4 (28 Nov 88)	8.5	55.7	45.8	6.0	8.7/3.0	2.7/3.0
5 (5 Dec 88)	9.5	54.2	54.2	7.5	7.2/7.2	0.3/0.3
6*	9.5	54.2	54.2	7.5	7.2/7.2	0.3/0.3
7*	9.5	54.2	54.2	7.5	7.2/7.2	0.3/0.3
8 (30 Dec 88)	10.5	73.0	62.5	18.0	13.0/13.0	0.0/0.0
9 (3 Jan 89)	10.5	71.7	62.5	18.0	13.0/13.0	0.0/0.0
10 (10 Jan 89)	10.5	74.0	62.5	18.0	13.0/13.0	0.0/0.0
11 (17 Jan 89)	12.0	79.2	75.0	18.5	13.0/13.0	0.0/0.0
12 (24 Jan 89)	11.5	83.3	70.8	17.0	13.0/13.0	0.0/0.0
13 (31 Jan 89)	11.5	79.1	70.8	17.0	13.0/13.0	0.0/0.0
14 (7 Feb 89)	10.5	71.0	62.5	16.5	13.0/13.0	0.0/0.0
15 (14 Feb 89)	11.5	78.1	70.8	17.5	13.0/13.0	0.0/0.0
16 (21 Feb 89)	11.0	77.9	66.7	18.5	13.0/13.0	0.0/0.0
17 (28 Feb 89)	11.0	71.6	66.7	18.0	13.0/13.0	0.0/0.0
18 (9 Mar 89)	11.0	75.3	66.7	16.5	13.0/13.0	0.0/0.0
19 (15 Mar 89)	11.5	80.1	70.8	17.5	13.0/13.0	0.0/0.0
20 (27 Mar 89)	0.0	(13)	87.9	0.0	(See note 13)	
21 (3 Apr 89)	10.0	58.3	60.0	9.0	11.3/13.0	2.3/4.0
22 (10 Apr 89)	11.5	70.8	77.6	18.0	13.0/13.0	0.0/0.0
23	0.0	(13)	84.4	0.0	(See note 13)	

(17 Apr 89)						
24	10.5	62.5	75.3	16.0	13.0/13.0	0.0/0.0
(24 Apr 89)						
25	10.0	58.3	70.8	13.5	11.3/13.0	1.7/0.0
(1 May 89)						
26	8.0	41.7	79.5	8.0	3.0/13.0	8.0/5.0
(8 May 89)						
27	10.5	62.5	72.3	15.0	13.0/13.0	0.0/0.0
(15 May 89)						
28	0.0	(13)	82.2	0.0	(See note 13)	
(22 May 89)						
29	0.0	(13)	76.9	0.0	(See note 13)	
(31 May 89)						

Notes:

1. Input Gauge is the pressure at the input to the controller as read by the calibrated pressure gauge.
2. Input Temp is the calculated input temperature "seen" by the controller. This temperature is based on the Input Gauge pressure using the following formula:

Input Temp = ((input press - 3)/12)(100oF)

3. Input Panel is the input temperature "seen" by the controller but measured by the panel meter via the electronic sensor.
4. Output Gauge is the actual output pressure from the controller as read by the calibrated pressure gauge.
5. Output Calib Gauge/Panel shows the pressure the controller should output when properly calibrated based on the input as measured by the gauge and the Panel respectively.
6. Calib-Actual Gauge/Panel shows the difference between the value the controller should output at proper calibration and what the controller is actually outputting based on the inputs as measured by the gauge and the Panel respectively.
7. Data could not be collected during weeks 6 and 7 because the Civil Engineering Controls Shop was calibrating the Variable Air Volume boxes during that time. Since the statistical analysis method employed by the researcher does not permit missed recordings, the data from week 5 was used for weeks 6 and 7.
8. The theoretical calibrated range of output from the controller is only 3-13 psi.
9. PB = ((TR*100)/Sensor Span)
10. Sensor Span = 0-100F for 3-15 PSI.
11. Pout = 8 + ((T-SP)/(TR)*CONTROLLER PRESSURE SPAN)
12. Pressure values were adjusted for the .5psi error in the calibrated gauge.

13. Outside air was above $60^{o}F$ which disabled the mixed air controller for summer conditions. For statistical data purposes, this data point will be recorded as zero drift.

Table 11. Data for Panel Mixed Air Controller

(Setpoint = 52.0oF, TR = 10oF)

Week (Date)	Setpoint (F)	MA Temp (F)	SP-Act	MA Vout (%)	MA Pout (psi)	RA%	OA%
1 (7 Nov 88)	52.1	52.1	0.0	38.0	8.0	4	84
2 (14 Nov 88)	52.0	51.9	.1	43.4	8.5	0	100
3 (18 Nov 88)	52.0	52.1	.1	48.2	9.5	0	100
4 (28 Nov 88)	52.1	52.2	.1	35.9	7.5	74	18
5 (5 Dec 88)	52.1	52.0	.1	39.0	8.0	6	86
6*	52.1	52.0	.1	39.0	8.0	6	86
7*	52.1	52.0	.1	39.0	8.0	6	86
8 (30 Dec 88)	52.1	52.1	0.0	44.2	8.5	0	65
9 (3 Jan 89)	52.1	52.0	.1	38.7	8.0	0	74
10 (10 Jan 89)	52.1	52.2	.1	47.4	9.0	0	72
11 (17 Jan 89)	52.1	52.2	.1	55.8	10.0	0	100
12 (24 Jan 89)	52.1	52.2	.1	96.6	15.0	0	100
13 (31 Jan 89)	52.2	52.1	.1	55.5	10.0	0	100
14 (8 Feb 89)	52.1	52.0	.1	36.7	8.0	26	55
15 (16 Feb 89)	52.1	52.2	.1	42.1	8.5	0	82
16 (21 Feb 89)	52.1	51.9	.2	41.2	8.5	0	90
17 (28 Feb 89)	52.1	52.2	.1	48.8	9.0	0	100
18 (9 Mar 89)	52.0	51.7	.3	46.0	9.0	0	100
19 (15 Mar 89)	52.0	51.9	.1	44.3	8.5	0	100
20 (27 Mar 89)	52.1	78.7	(6)	96.7	15.0	0	100
21 (3 Apr 89)	52.1	53.2	1.1	95.8	15.0	0	100
22 (10 Apr 89)	52.2	51.9	.3	45.2	8.5	0	100
23 (17 Apr 89)	52.2	66.8	(6)	96.7	15.0	0	100
24 (24 Apr 89)	52.2	62.8	(6)	96.0	15.5	0	100
25	52.2	53.7	(6)	95.7	15.0	0	100

(1 May 89)							
26	52.2	63.3	(6)	96.0	14.5	0	100
(8 May 89)							
27	52.2	60.2	(6)	95.9	15.0	0	100
(15 May 89)							
28	52.2	64.7	(6)	96.4	15.0	0	100
(22 May 89)							
29	52.2	77.1	(6)	21.0	5.5	100	18
(31 May 89)			(Minimum Outside Air Settings)				

Notes:

1. SP-Act is the difference between the setpoint temperature and the actual temperature to which the controller is controlling.
2. MA Vout (%) is the voltage percentage as sent to the electronic-to-pneumatic transducer from the controller.
3. MA Pout (psi) is the pressure from the electronic-to-pneumatic transducer as measured by the pressure gauge in the Panel.
4. RA% and OA% are the percentage of return air and outside air as measured by the meters in the Panel. These are not actual percentages because the system does not have positive positioners. They are based on the resistance in the position indicators mounted to the actuators.
5. Data could not be collected during weeks 6 and 7 because the Civil Engineering Controls Shop was calibrating the Variable Air Volume boxes during that time. Since the statistical analysis method employed by the researcher does not permit missed recordings, the data from week 5 was used for weeks 6 and 7.
6. Temperature difference on this date is not an indicator of controller performance due to outside air temperature. Data will be recorded as zero drift for statistical calculations because controller output is correct.

Table 12. Data For Built-Up System Supply Air Controller

(Setpoint = 55oF, PB = 10, TR = 10oF)

Week (Date)	Input Gauge (PSI)	Input Temp (F)	Input Panel (F)	Output Gauge (PSI)	Output Calib Gauge /Panel (PSI)	Calib-Actual Gauge /Panel (PSI)
1 (7 Nov 88)	5.5	60.8	64.5	14.0	13.0/13.0	0.0/0.0
2 (14 Nov 88)	5.5	60.8	62.4	12.5	13.0/13.0	0.5/0.5
3 (21 Nov 88)	5.5	60.8	62.7	14.5	13.0/13.0	0.0/0.0
4 (28 Nov 88)	5.5	60.8	63.4	13.0	13.0/13.0	0.0/0.0
5 (5 Dec 88)	5.5	60.8	63.3	15.0	13.0/13.0	0.0/0.0
6*	5.5	60.8	63.3	15.0	13.0/13.0	0.0/0.0
7*	5.5	60.8	63.3	15.0	13.0/13.0	0.0/0.0
8 (30 Dec 88)	7.0	73.3	76.3	18.0	13.0/13.0	0.0/0.0
9 (3 Jan 89)	7.0	73.3	76.2	18.0	13.0/13.0	0.0/0.0
10 (10 Jan 89)	7.5	77.5	77.4	18.0	13.0/13.0	0.0/0.0
11 (17 Jan 89)	8.0	81.7	82.4	19.0	13.0/13.0	0.0/0.0
12 (24 Jan 89)	8.5	85.8	86.4	18.5	13.0/13.0	0.0/0.0
13 (31 Jan 89)	8.0	81.7	82.4	17.5	13.0/13.0	0.0/0.0
14 (7 Feb 89)	7.0	73.3	75.0	17.5	13.0/13.0	0.0/0.0
15 (14 Feb 89)	8.0	81.7	81.3	18.0	13.0/13.0	0.0/0.0
16 (21 Feb 89)	8.0	81.7	81.2	18.0	13.0/13.0	0.0/0.0
17 (28 Feb 89)	7.0	73.3	75.5	18.0	13.0/13.0	0.0/0.0
18 (9 Mar 89)	7.5	77.5	78.5	18.0	13.0/13.0	0.0/0.0
19 (15 Mar 89)	8.0	81.7	83.3	17.0	13.0/13.0	0.0/0.0
20 (27 Mar 89)	9.0	90.0	90.7	18.0	13.0/13.0	0.0/0.0
21 (3 Apr 89)	6.0	65.0	64.5	14.0	13.0/13.0	0.0/0.0
22 (10 Apr 89)	8.0	81.7	80.7	17.5	13.0/13.0	0.0/0.0
23	8.5	85.8	87.6	18.5	13.0/13.0	0.0/0.0

(17 Apr 89)						
24	7.5	77.5	78.2	16.0	13.0/13.0	0.0/0.0
(24 Apr 89)						
25	7.0	73.3	73.0	18.5	13.0/13.0	0.0/0.0
(1 May 89)						
26	8.0	81.7	82.2	18.0	13.0/13.0	0.0/0.0
(8 May 89)						
27	7.0	73.3	75.1	17.0	13.0/13.0	0.0/0.0
(15 May 89)						
28	8.0	81.7	84.0	16.5	13.0/13.0	0.0/0.0
(22 May 89)						
29	5.0	56.7	58.9	8.5	9.7/11.9	1.2/3.4
(31 May 89)						

Notes:

1. Input Gauge is the pressure to the controller from the sensor as read by a gauge mounted on the controller. This gauge was not calibrated by the researcher. It was installed as part of the system by the Civil Engineering Controls Shop.
2. Input Temp is the temperature calculated from Input Gauge using the following formula:

$$\text{Input Temp} = ((\text{input press} - 3)/12)(100^{\circ}F) + 40^{\circ}F$$

3. Input Panel is the temperature "seen" by the controller as measured by the Panel via the electronic sensor.
4. Output Gauge is the output pressure from the controller as measured by the calibrated gauge.
5. Output Calib Gauge/Panel shows the pressure the controller should output when properly calibrated based on the input as measured by the gauge and the Panel respectively.
6. Calib-Actual Gauge/Panel shows the difference between the value the controller should output at proper calibration and what the controller is actually outputting based on the inputs as measured by the gauge and the Panel respectively.
7. Data could not be collected during weeks 6 and 7 because the Civil Engineering Controls Shop was calibrating the Variable Air Volume boxes during that time. Since the statistical analysis method employed by the researcher does not permit missed recordings, the data from week 5 was used for weeks 6 and 7.
8. The theoretical calibrated range of output from the controller is only 3-13 psi.
9. PB = ((TR*100)/Sensor Span)
10. Sensor Span = 40-140°F for 3-15 PSI.
11. Pout = 8 + ((T-SP)/(TR)*CONTROLLER PRESSURE SPAN)
12. Pressure values were adjusted for the .5psi error in the calibrated gauge.

13. Actual PB = 10 which is consistent with the equation in Note 9. Drawing in Appendix C shows PB = 8 which is the mechanical setting on the controller.

Table 13. Data For Panel Supply Air Controller

(Setpoint = 55oF, TR = 10)

Week (Date)	Setpoint (F)	SA Temp (F)	SA Vout (%)	Calib Vout	Calib-Act Vout	SA Pout (psi)
1 (7 Nov 88)	54.9	59.6	103.1	97.0	3.0	15.5
2 (14 Nov 88)	54.9	58.4	89.5	85.0	4.5	14.0
3 (18 Nov 88)	54.9	58.8	94.0	89.0	5.0	14.5
4 (28 Nov 88)	55.0	60.8	103.1	100.0	0.0	15.5
5 (5 Dec 88)	55.0	60.5	103.2	100.0	0.0	15.5
6*	55.0	60.5	103.2	100.0	0.0	15.5
7*	55.0	60.5	103.2	100.0	0.0	15.5
8 (30 Dec 88)	55.0	60.0	103.2	100.0	0.0	15.5
9 (3 Jan 89)	55.0	60.4	103.3	100.0	0.0	15.5
10 (10 Jan 89)	55.0	60.2	103.2	100.0	0.0	15.5
11 (17 Jan 89)	55.0	57.7	79.5	77.0	2.5	13.0
12 (24 Jan 89)	55.0	57.7	80.7	77.0	3.7	13.0
13 (31 Jan 89)	55.0	57.8	80.8	78.0	2.8	13.0
14 (8 Feb 89)	55.0	59.7	103.2	97.0	3.0	15.5
15 (16 Feb 89)	55.0	59.0	95.4	90.0	5.4	14.5
16 (21 Feb 89)	55.0	58.0	83.6	80.0	3.6	13.0
17 (28 Feb 89)	55.0	58.0	84.5	80.0	4.5	13.5
18 (9 Mar 89)	54.9	60.1	103.1	100.0	0.0	15.5
19 (15 Mar 89)	55.0	58.7	92.4	87.0	5.4	14.5
20 (27 Mar 89)	55.0	82.4	103.6	100.0	0.0	15.5
21 (3 Apr 89)	54.9	59.0	96.2	91.0	5.2	15.0
22 (10 Apr 89)	54.9	58.7	92.7	88.0	4.7	14.5
23 (17 Apr 89)	55.0	72.9	103.6	100.0	0.0	15.5
24 (24 Apr 89)	54.9	66.5	103.0	100.0	0.0	15.5
25	54.9	58.3	88.2	84.0	4.2	14.0

(1 May 89)						
26	54.9	66.9	103.0	100.0	0.0	15.5
(8 May 89)						
27	54.9	63.9	102.9	100.0	0.0	15.5
(15 May 89)						
28	54.9	84.0	103.3	100.0	0.0	15.5
(22 May 89)						
29	54.9	59.0	96.5	91.0	5.5	15.0
(31 May 89)						

Notes:

1. SA Temp is the temperature "seen" by the controller as measured by the Panel meter via electronic sensor.
2. SA Vout is the percentage of voltage output from the controller based on the temperature input.
3. Calib Vout is the voltage the controller should output if it were properly calibrated based on the input temperature. It is based on a 10oF TR, Calib Vout = 50% + (10% Vout/oF * (Temp Act - SP)).
4. Calib-Act Vout is the difference between the calibrated controller voltage percentage and the actual output.
5. SA Pout is the pressure the controller outputted through the electronic-to-pneumatic transducer.
6. Data could not be collected during weeks 6 and 7 because the Civil Engineering Controls Shop was calibrating the Variable Air Volume boxes during that time. Since the statistical analysis method employed by the researcher does not permit missed recordings, the data from week 5 was used for weeks 6 and 7.

Table 14. Additional Data Collected on Built-Up System but not Compared to Panel

Week (Date)	Changeover Input (psi)	Changeover Output (psi)	Static Pressure Input (psi)	Static Pressure Output *(psi)	HW Converter Input1 *(psi)	HW Converter Input2 (psi)	HW Converter Output *(psi)
1 (7 Nov 88)	7.0	.0	9.5	6.5	12.0	5.0	7.0
2 (14 Nov 88)	8.0	0.0	11.0	8.0	12.5	5.0	8.0
3 (21 Nov 88)	8.0	0.0	11.5	7.5	12.0	5.5	8.5
4 (28 Nov 88)	7.5	0.0	11.5	6.5	12.5	6.0	8.5
5 (5 Dec 88)	7.5	0.0	11.5	6.5	12.5	8.5	6.5
6 (30 Dec 88)	7.5	0.0	9.5	9.5	13.0	5.5	8.5
7 (3 Jan 89)	8.0	0.0	9.5	7.5	13.0	7.0	9.0
8 (10 Jan 89)	7.5	0.0	9.5	13.5	13.0	6.0	10.0
9 (17 Jan 89)	9.0	0.0	9.5	14.5	13.5	6.0	18.5
10 (24 Jan 89)	9.5	0.0	9.0	15.0	14.0	6.0	19.0
11 (31 Jan 89)	8.0	0.0	8.5	15.5	14.0	5.5	17.5
12 (7 Feb 89)	7.0	0.0	9.5	9.0	13.0	5.5	8.0
13 (14 Feb 89)	8.5	0.0	9.0	9.0	13.5	5.0	17.0
14 (21 Feb 89)	8.0	0.0	9.5	9.5	13.5	5.0	18.0
15 (28 Feb 89)	7.5	0.0	9.0	8.5	13.0	5.5	8.0
16 (9 Mar 89)	8.0	0.0	7.0	17.0	13.0	5.5	13.0
17 (15 Mar 89)	8.0	0.0	9.5	9.0	14.0	6.0	20.0
18 (27 Mar 89)	10.5	15.5	9.5	9.0	14.5	6.5	20.0
19 (3 Apr 89)	9.0	0.0	10.0	(3)	12.0	4.5	0.0
20 (10 Apr 89)	8.5	0.0	9.5	9.0	13.5	5.0	8.5
21 (17 Apr 89)	10.0	8.5	10.0	9.5	14.0	6.0	9.5
22 (24 Apr 89)	9.5	4.5	9.5	8.5	13.0	4.5	12.0
23 (1 May 89)	9.0	0.0	(4)	(4)	13.0	4.4	4.4
24	9.5	6.5	9.5	9.0	13.5	5.0	20.0

(8 May 89)							
25	9.5	0.0	9.5	8.5	13.0	4.5	8.0
(15 May 89)							
26	10.0	5.0	9.0	15.5	14.0	5.0	19.0
(22 May 89)							
27	10.5	17.0	9.5	9.0	13.0	4.5	14.5
(31 May 89)							

Notes:
1. Pressure values are adjusted for gauge error of .5 psi.
2. * indicates gauges which were existing on equipment or installed during experiment by personnel other than the researcher. These starred gauges were not tested or calibrated by the researcher.
3. Controller did not stabilize within 15 minutes. Controller was "hunting" between 7 and 10psi.
4. Controller did not stabilize within 15 minutes. Sensor varied between 9 and 11psi. Controller "hunted" between 1 and 15psi.

Table 15. Additional Data Collected on the Panel but Not Compared to the Built-up System

Week (Date)	RA Temperature (F)	OA Temperature (F)
1 (7 Nov 88)	67.5	37.4
2 (14 Nov 88)	67.6	46.3
3 (18 Nov 88)	67.2	47.0
4 (28 Nov 88)	68.6	31.5
5 (5 Dec 88)	71.4	32.5
6 (30 Dec 88)	69.9	26.7
7 (3 Jan 89)	69.6	31.8
8 (10 Jan 89)	72.4	26.7
9 (17 Jan 89)	74.8	49.2
10 (24 Jan 89)	81.5	52.4
11 (31 Jan 89)	75.2	48.6
12 (8 Feb 89)	69.1	9.2
13 (16 Feb 89)	72.5	31.6
14 (21 Feb 89)	70.8	38.4
15 (28 Feb 89)	70.8	42.7
16 (9 Mar 89)	71.4	40.9
17 (15 Mar 89)	76.7	38.6
18 (27 Mar 89)	88.8	81.1
19 (3 Apr 89)	64.2	52.6
20 (10 Apr 89)	73.0	41.5
21 (17 Apr 89)	85.3	68.0
22 (24 Apr 89)	72.1	64.3
23 (1 May 89)	67.7	53.3
24 (8 May 89)	78.2	63.2

25 (15 May 89)	70.2	60.0
26 (22 May 89)	81.7	66.1
27 (31 May 89)	73.9	86.8

(Note: These return air temperatures were after panel control of times varying from .5 hours to 1 week. Temperatures in excess of 72°F were taken before Panel SA temperatures could lower space temp.)

Table 16. Additional Data Collected on the Built-Up System Via Panel

Week (Date)	RA Temperature (F)	OA Temperature (F)
1 (7 Nov 88)	67.6	37.4
2 (14 Nov 88)	68.2	45.0
3 (21 Nov 88)	67.3	36.5
4 (28 Nov 88)	68.4	32.0
5 (5 Dec 88)	71.1	31.3
6 (30 Dec 88)	74.8	26.7
7 (3 Jan 89)	73.0	35.1
8 (10 Jan 89)	75.6	30.9
9 (17 Jan 89)	82.1	52.9
10 (24 Jan 89)	86.3	57.5
11 (31 Jan 89)	82.2	48.6
12 (8 Feb 89)	73.2	17.5
13 (16 Feb 89)	80.1	38.7
14 (21 Feb 89)	80.2	44.7
15 (28 Feb 89)	72.5	29.4
16 (9 Mar 89)	76.9	46.4
17 (15 Mar 89)	82.1	41.3
18 (27 Mar 89)	89.6	81.4
19 (3 Apr 89)	78.1	65.0
20 (10 Apr 89)	78.9	47.6
21 (17 Apr 89)	85.3	71.2
22 (24 Apr 89)	76.0	67.4
23 (1 May 89)	70.4	55.0
24 (8 May 89)	80.0	65.6

25 (15 May 89)	72.1	63.7
26 (22 May 89)	82.7	65.8
27 (31 May 89)	73.9	86.8

(Note: These return air temperatures were after built-up system control of times varying from .5 hours to 1 week.)

Assumptions. Prior to performing regression analysis, the following assumptions are required:

1) Linearity of the sample data

2) Variable-x (time or observations) is fixed. Variable-y is random.

3) Variables are measured on an interval or ratio scale.

x-time (weeks), y-drift (PSI, degrees Fahrenheit, voltage)

4) The model $y = Beta0 + (Beta1)x + e$ can be used where Beta0 is the y-intercept

Expected value of the error terms-e is zero.

Error terms are independent.

Y-values have an equal variance and are normally distributed about the regression line.

5) The equation $yhat = Betahat0 + (Betahat1)x$ can be used as an estimate of the true regression line $E(y) = Beta0 + (Beta1)x$.

6) The factor-time will include all other factors which initiate drift of the controls.

Aptness of assumption 4) will be assessed in the Data Analysis section of this study.

Data Analysis. The absolute value of the differences between the actual and calibrated values measured on each date for the particular system components were entered into the QUATTRO and STATISTIX statistical software packages (see Appendices D and E). Regression analysis and scatter plots of the drift versus obs (observations, or time (Figures 15-20)), scatter plots of predicted versus residual values, and rankit plots of the residual values were done on each set of data. Based on regression analysis output, approximate regression lines were drawn on the drift versus obs scatter plots (Figures 15-20). This information is described in detail in the next sections. The computer output is in Appendices D and E.

<u>**Qualitative Analysis of the Built-Up System**</u>. The performance measurements for this system were taken using two methods to improve internal validity. The first method was to take pressure measurements from the controller input and output ports using an air pressure gauge. This gauge was calibrated in September 1988, but is limited in accuracy due to a readable scale of plus or minus one-half psi. The second method was to measure the same variable from the Standard Panel. While this second method assumes the sensor system for the Panel remains accurate -- something this research is attempting to validate -- the use of the sensors to verify built-up system performance and avoid false statements about that performance warrants Panel use. Additionally, the sensor accuracy was verified to be within 0.7oF during installation and within 0.4oF after the last data were collected.

The data collected from the pressure gauge on the mixed air controller appears to be accurate. The calculated slope (Beta1) was .001psi/week which, at a 10oF TR translates into a .001oF/week drift. This Beta1 value was not statistically significant with a p-value of .96. The assumption of equal variances was not confirmed nor was the assumption of normally distributed error terms. The equation obtained from this analysis was the following (see Figure 15):

Drift (oF) = .533oF + ((.001oF/week) * time(weeks))

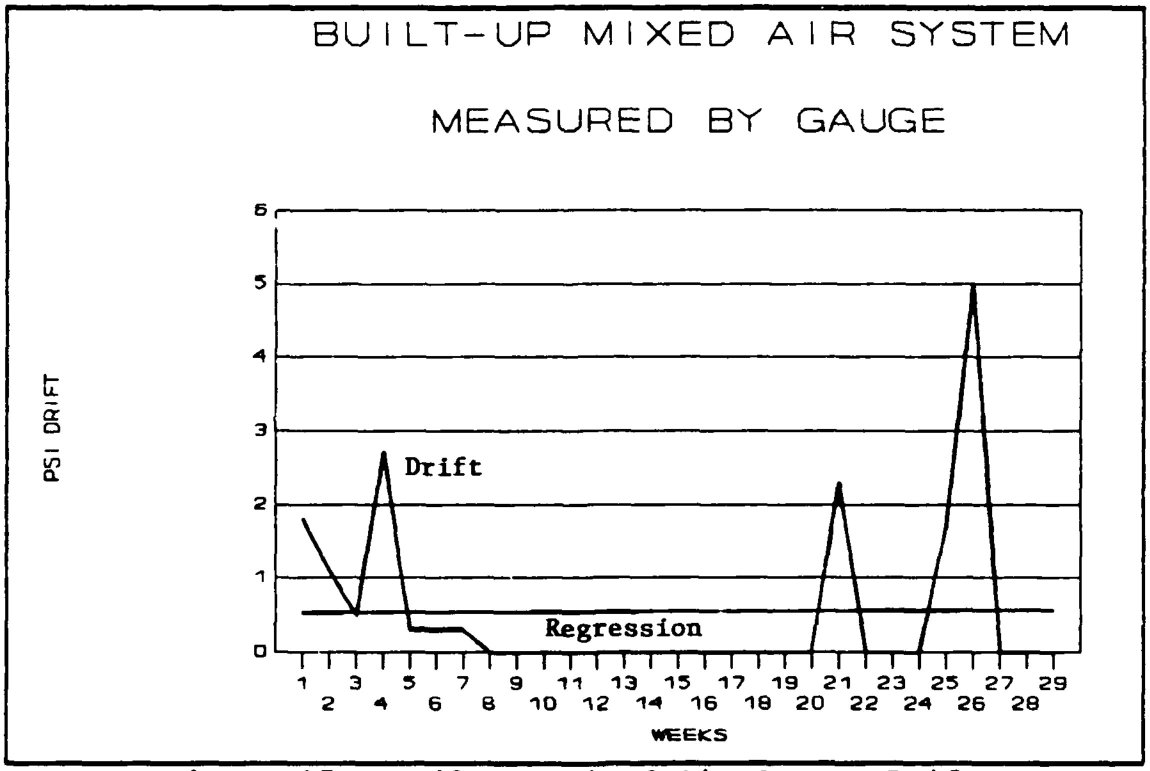


Figure 15. Built-Up Mixed Air System Drift
(Measured by Gauge)

The data on the built-up system mixed air controller collected via the Panel in temperatures also indicates the controller was accurate. The calculated slope (Beta1) was -.021psi/week which, at a 10oF TR translates into a -.021oF/week drift. The Beta1 value was not statistically significant with a p-value of .55. The assumption of equal variances was not confirmed nor was the assumption of normally distributed error terms. The equation obtained was the following (see Figure 16):

Drift (oF) = .992oF - ((.021oF/week) * time(weeks))

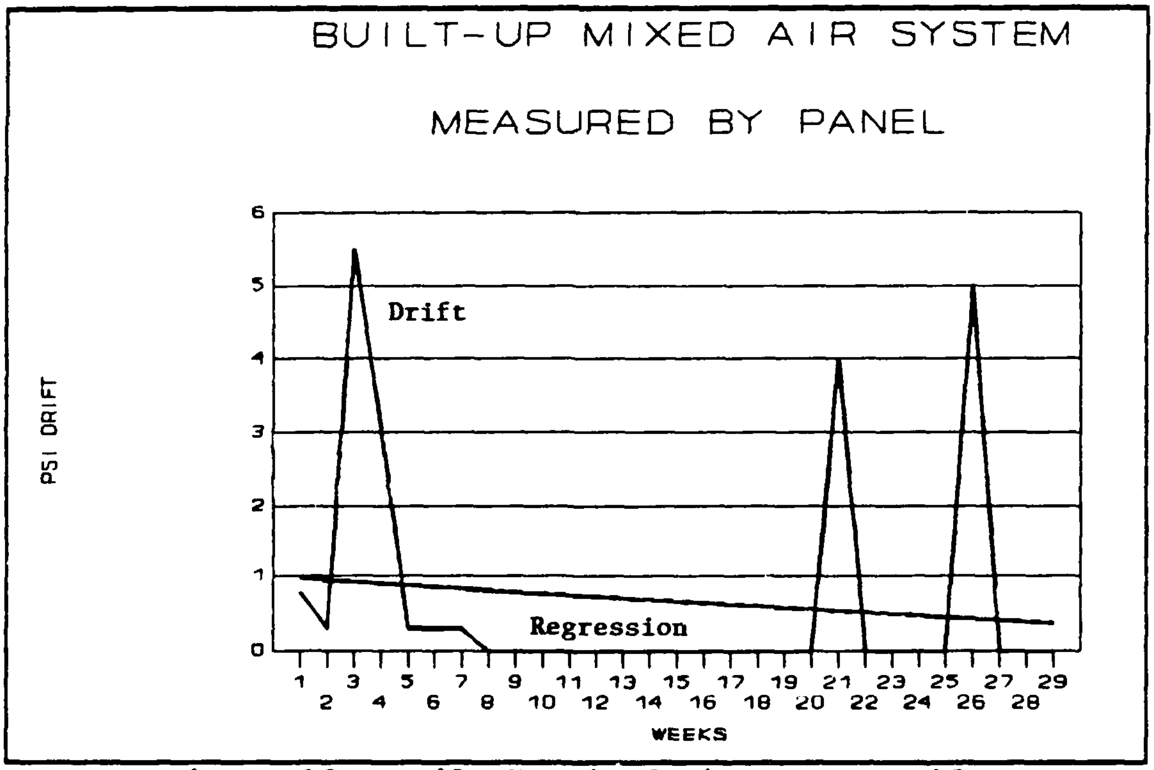


Figure 16. Built-Up Mixed Air System Drift (Measured by Panel)

The data collected on the built-up system supply air controller is similar to that of the mixed air controller. The calculated slope (Beta1) from the gauge measurements was .005psi/week which, at a 10oF TR translates into a .005oF/week drift. The equation obtained from these measurements was the following (see Figure 17):

Drift (oF) = -.017oF + ((.005oF/week) * time(weeks))

The Beta1 value was not statistically significant with a p-value of .35. Neither the assumption of equal variances nor the assumption of normally distributed error terms was confirmed.

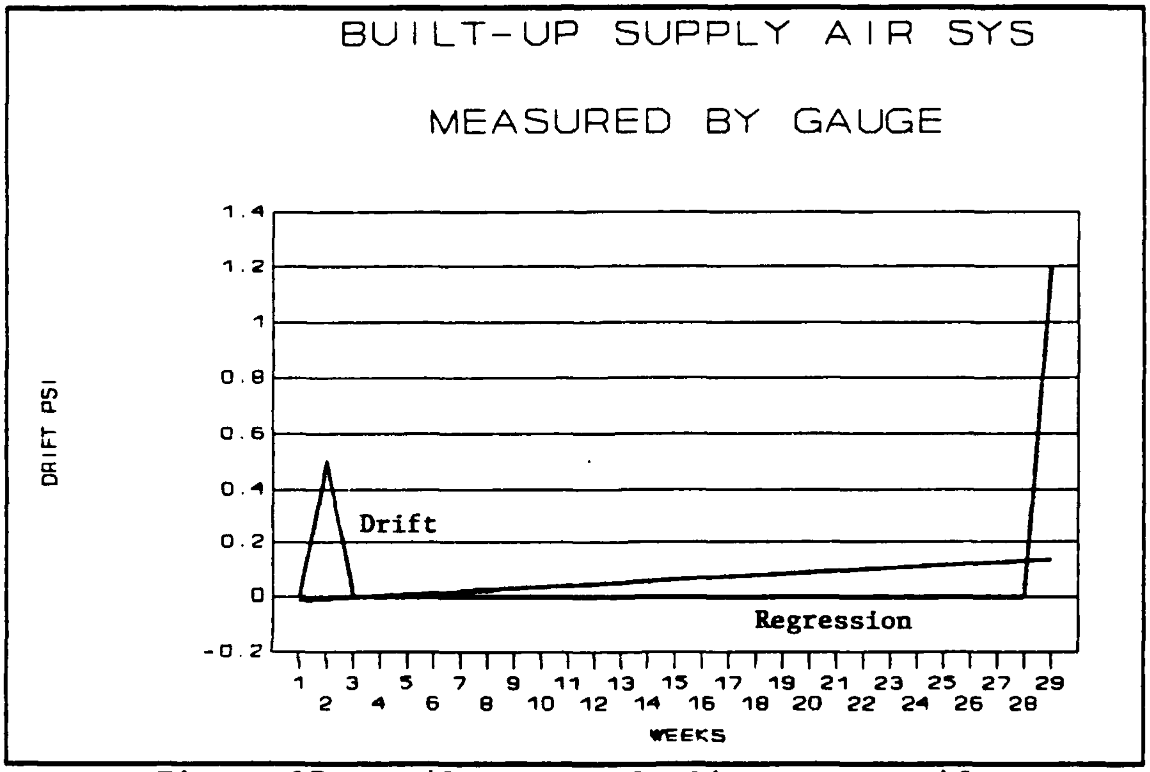


Figure 17. Built-Up Supply Air System Drift (Measured by Gauge)

The calculated slope (Beta1) for the built-up system from the Panel measurements was -.021psi/week which, at a 10oF TR translates into a -.020oF/week drift. The equation obtained from these measurements was the following (see Figure 18):

Drift (oF) = -.169oF + ((.020oF/week) * time(weeks))

The Beta1 value was not statistically significant with a p-value of .15. Neither the assumption of equal variances nor the assumption of normally distributed error terms was confirmed.

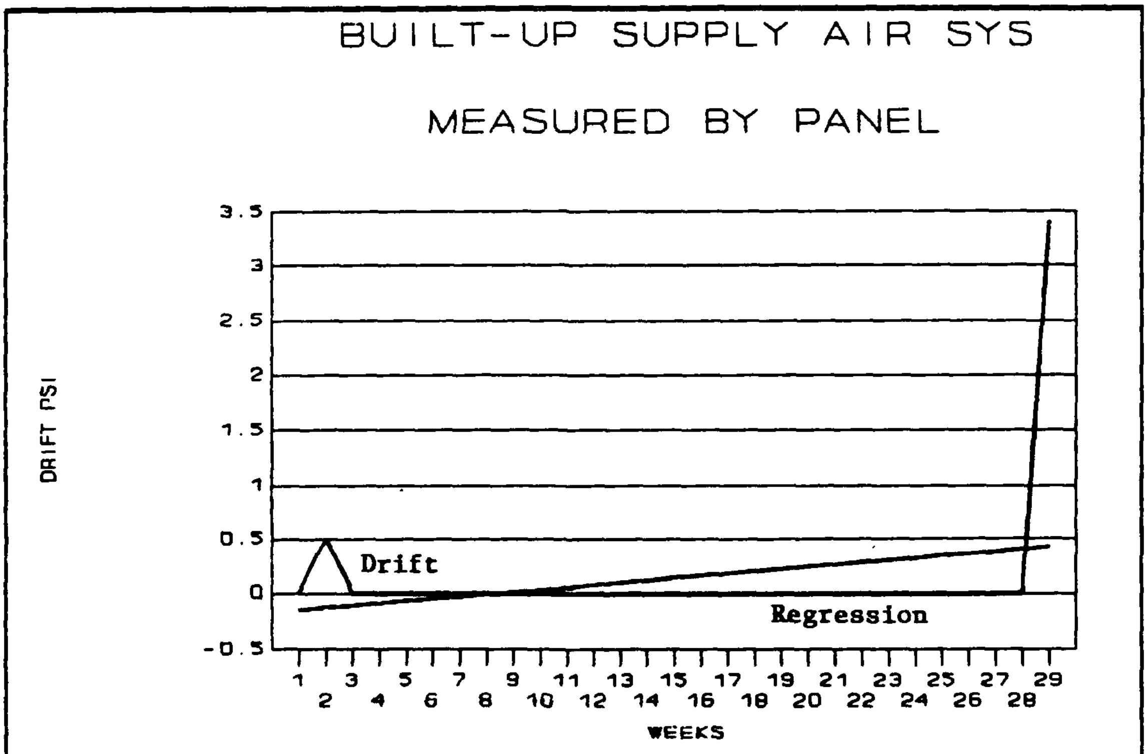


Figure 18. Built-Up Supply Air System Drift (Measured by Panel)

Qualitative Analysis of the Standard Panel. The data collected on the mixed air controller of the Standard Panel system was similar to that of the built-up system. The calculated slope (Beta1) was .001oF/week. This value was not statistically significant with a p-value of .83. The assumptions of equal variances and normally distributed error terms were not confirmed. The equation obtained was the following (see Figure 19):

Drift (oF) = 0.102oF + ((0.001oF/week) * (time(weeks))

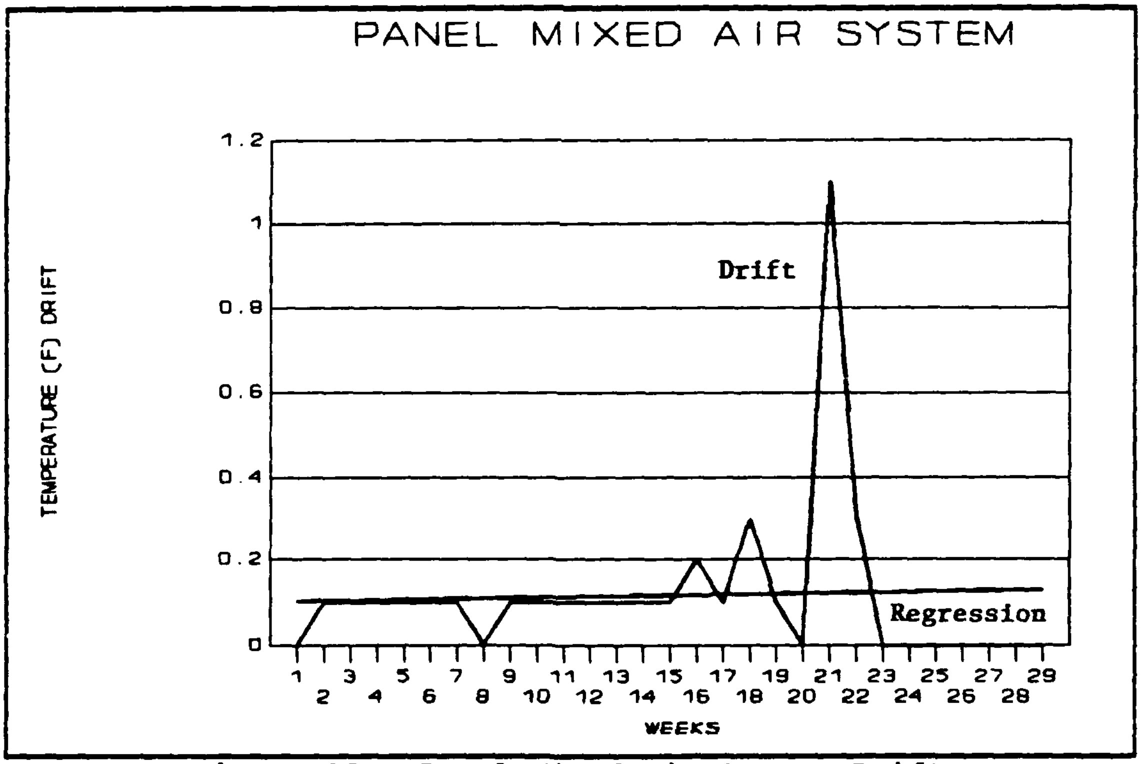


Figure 19. Panel Mixed Air System Drift

The data collected for the supply air controller indicate it will have a calculated slope (Beta1) of .097%Vout/week which, at a 10oF TR translates into a .0097oF/week drift. The Beta1 value was statistically significant with a p-value of .05. The data also confirms both the equal variances and normally distributed error terms assumptions. The equation obtained was the following (see Figure 20):

Drift (oF) = 1.216 + ((0.0097oF/week) * (time(weeks))

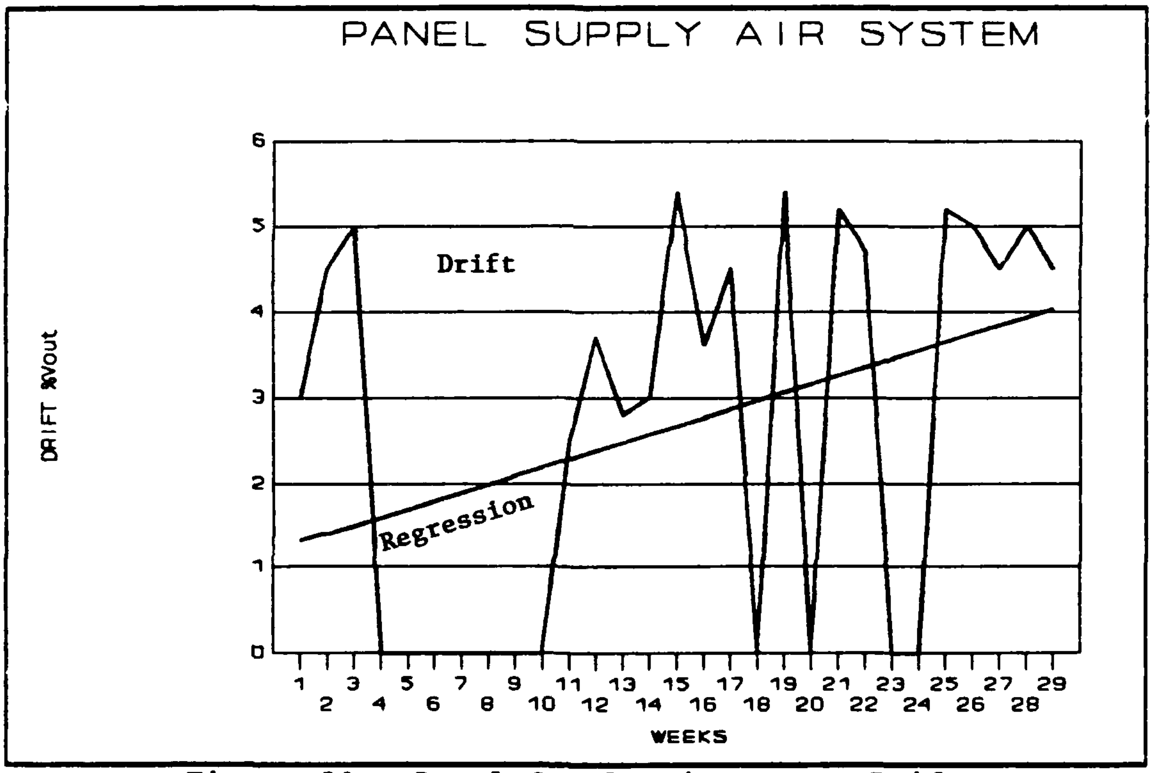


Figure 20. Panel Supply Air System Drift

Quantitative Analysis -- Comparison. The regression equations, t-statistics, and associated p-values for this comparison are in Appendix E. First the MA controllers were compared. When the data measured via the gauge on the built-up system was analyzed with the Panel data, the Beta3 value, OBSP, was not statistically significant. When the data measured via the Panel on the built-up system was analyzed with the Panel data, the Beta3 value was also not statistically significant. The respective p-values were .99 and .53. In both cases, the assumptions of equal variances and normally distributed error terms were not confirmed.

Next the SA controllers were compared. When the data measured via the gauge on the built-up system was analyzed with the Panel data, the Beta3 value was not statistically significant. The assumption of equal variances was not confirmed but the assumption of normally distributed error terms was confirmed. When the data measured via the Panel on the built-up system was analyzed with the Panel data, the Beta3 value was also not statistically significant. The respective p-values for the gauge and panel data were .52 and .38. Neither the assumption of equal variances nor the assumption of normally distributed error terms was confirmed.

Limitations. The lack of statistically significant regression terms must be tempered with the knowledge that the data was collected over only 29 weeks. The effects of long-term drift cannot accurately be predicted from such a short period of time and without an entire year of activity.

Additionally, actual controller input values were used to evaluate the overall operability of the system each week, as opposed to artificially introduced values. Although an overall impression of the operating system can be obtained from these values, they often exceeded the operating range of the controller forcing the controller to produce a maximum output and requiring the researcher to record zero drift. It is possible, therefore, that the zero drift recorded on these occasions affected the calculated drift and comparison values for each system.

The final limitation is a restatement of the limitations on the measurement instruments. Although neither system appeared to be more reliable thus far, the fact that the drift measured could have just as well been mere fluctuations in the meter (0.1-0.2oF) or gauge inaccuracy (plus or minus 0.5psi) precludes the making of an all-inclusive statement.

Delphi Method

To improve the external validity of this research, a Delphi survey was conducted to obtain the opinions of experts concerning the Air Force Standard Panel. The survey was conducted in three rounds using eight experts. The purpose of the first round was to obtain general information and was conducted over the telephone. All eight experts participated in round one. The second and third rounds were conducted via the mail. The purpose of the last two rounds was to refine the information gathered in round one and to reach a consensus on the major issues. Six experts responded to the surveys from round two. Eight surveys were sent out for round three but only four responses were received. Follow-up phone calls and letters were sent to the experts who did not respond within one month, six weeks and eight weeks. The follow-ups were marginally successful. Based on the agreement in round two on a majority of issues and the lack of serious disagreement among the respondents to round three, it is not believed that the 50% response rate for round three is detrimental to this research.

The cover letters and compiled packages which were sent to the respondents for rounds two and three are in Appendices F and G, respectively. The prefaces, questions and results of all three rounds have been collected and formatted in the same order as the questionnaire in the following paragraphs. Like responses were grouped where possible to clarify the presentation and show consensus. Specific round three responses are also presented. However, the majority of the letters reflect agreement with the text from round two.

<u>AREA 1: YOUR EXPERIENCE</u>. The ranges of experience were discussed and recorded by hand during the telephone

interview (round one) and recorded from the written responses for round two. The information obtained indicates a wide variety of expertise with extensive experience -- factors which greatly increase the validity of the research results. The impact of this information on the research is to guarantee all phases of the life cycle of the Panel are looked at, analyzed, and compared with similar phases of other control systems.

Question 1. What phase(s) of the life of the Control Panel(s) have you been involved in and what was your function during that phase? Also, how long did you work with the Panel(s) during each phase? (The second question was not asked during round one.)
(More than one answer is possible.)

Responses from rounds one and two were combined for this question since the responses are not opinions. These responses are as follows.

One expert hired the consulting engineering company, selected the Panel for the particular application, was involved in the design, and supervises technicians who maintain the Panel.

Two experts worked with the Panel in the design, installation, and operations and maintenance phases.

Two experts have been involved with the Panel from development (after CERL wrote the controller specification), which included review of the Design Instructions and

Technical Specifications and testing, through present-day installations and operations and maintenance applications for which they provide consultation. One of these experts has worked with the Panel for five years, the other for over three years.

One expert provided technical assistance for three weeks during the installation of the Panel and was kept informed about any problems which occurred during the operations and maintenance phase of the same Panel, which has been functioning for about six months.

One expert has been involved with the Panel for two years. He was concerned with marketing, applications selections during the design phase, supervision during installations, and training and supervision during operations and maintenance.

One expert supervised HVAC, structural and electrical personnel in facility and equipment operations and maintenance for five years and was involved with the Panel for about a year.

No responses were required for round three.

AREA 2: TYPE OF PANEL. During the telephone interview, only the Hot Water Temperature Control (#4 below), Variable Air Volume (VAV) Temperature Control (#3 below), Static Pressure Control for Inlet Vane Damper System (#2 below), and Multizone Control (#8 below) Panels were reported in operation (see round one responses below). All eight types have been designed and could be manufactured. This question was asked during rounds one and two to ensure information accuracy and include possible new information.

<u>Question 2</u>. What types of Panels have you worked with during any phase of Panel life, inception through operations and maintenance? (More than one answer is possible.)

1. Static Pressure Control Panel for Fan Speed Control (FSC) System
2. Static Pressure Control Panel for Inlet Vane Damper (IVD) System
3. Variable Air Volume (VAV) Temperature Control Panel
4. Hot Water Temperature Control Panel
5. Temperature Control Panel for Single Zone System with One Controller
6. Temperature Control Panel for Single Zone System with Cascade Control
7. Temperature and Humidity Control Panel for Single Zone System
8. Multizone Control Panel
9. A custom-built Panel designed, constructed and installed according to ETL 83-1, Change 1. (Note: If you select this type of Panel as your response, please describe the function, application and construction of your Panel.)

Except for the additional comments, responses from rounds one and two were combined for this question because the responses are not opinions. The results are shown in the following chart.

PANEL TYPE	NUMBER OF EXPERTS WHO HAVE WORKED ON THE PANEL	PHASE DURING WHICH THE EXPERT WORKED ON THE PARTICULAR PANEL
1		
	2	development
	4	design
	2	installation
	2	operations and maintenance
2		
	2	development
	4	design
	5	installation
	5	operations and maintenance
3		
	2	development
	4	design
	5	installation
	5	operations and maintenance

4		
	2	development
	4	design
	4	installation
	4	operations and maintenance
5		
	2	development
	4	design
	2	installation
	2	operations and maintenance
6		
	2	development
	4	design
7		
	2	development
	4	design
	2	operations and maintenance
8		
	2	development
	4	design
	4	installation
	4	operations and maintenance

9		
	1	design
	1	installation
	1	operations and maintenance

Additional Comments.

One expert had

> ...seen projects requiring panel 6 but has always recommended using a panel similar to 5 in its place...[This expert's] type 9 panels have all been similar to the Standard Panels with additional functions added by the designer to make them compatible with the mechanical systems, i.e., building pressure control, fan H-O-A switches, electronic output to actuators for small projects, etc. The `special' panels usually add more cost to the project than their true value provides, i.e., new engineering, drafting and special assembly costs just to add H-O-A switches is not cost effective.

No responses were required for this question in round three.

AREA 2: TYPE OF PANEL (Continued).

Question 3. Understanding that the Panel may be used as part of a retrofit project as well as new HVAC projects, what types of sensors, actuators, and controllers (electronic, pneumatic, DDC) does (do) the Panel(s) from your responses to question 2 work with?

Responses from rounds one and two were combined for this question because the responses are not opinions. All Panels from all experts worked with electronic PI controllers, RTD temperature sensors and/or differential pressure transmitters (for static pressure, fan speed control or humidity control) according to ETL 83-1, Change 1. Also, the Panels used pneumatic actuators on most projects, but electronic actuators were used on small projects where an air compressor is not cost effective.

No responses were required for round three since 100% agreement existed during round two.

AREA 3: DESIGN PHASE. During the design phase, areas of concern are (1) the Panel's adaptability to the overall HVAC system under design compared to other control systems and (2) the involvement of the architect/engineer if applicable.

Question 4. What were your experiences with the Air Force Standard Panel during the design of the entire HVAC system? Additionally, what type of system did it replace, what alternative control systems were investigated, and what caused you to select a Panel for your application? (The second question was not asked during round one.) (If this is not applicable to you, please feel free to consult co-workers who may have had more experience. If this is done, please record the individual's name, job title, and experience with the Panel in a format similar to survey question 1. Remember, the research is an effort to obtain as much information as possible and disseminate it to all the experts.)

Round One Responses. One expert indicated the Corps of Engineers have the Panel on the AutoCAD design software package and the specification verbiage is in the HVAC Technical Specification manual. This combination allows for easy design.

One expert mentioned that, although the specifications or statements of work in a project may call for an Air Force Standard Control Panel, architects/engineers and contractors continue to make value engineering proposals for a different control scheme. Many of these proposals are being accepted at base level. This expert also mentioned that the Army is using a similar concept in their Control Panels. However, instead of using analog controllers, their Panels will use industrial-grade, single-loop microprocessor controllers. Each microprocessor can be programmed to control any type of loop -- hot water control, VAV, etc. The advantage of this scheme is that only one Panel is required, regardless of the loops involved in the HVAC system, because many microprocessors can fit into a small space. With the Air Force Panel, more control loops mean more Panels.

One expert indicated that designers have a general reluctance to sign off on the control system design because it is not truly their own. This expert also believes industrial-grade components are not required, only commercial grade. This expert does not favor the particular specification method used in the HVAC Technical Specifications. Instead, this expert believes a performance specification would yield better products.

One expert believes many of the Panel functions could be removed from the Panel specifications and be performed by the base energy monitoring and control system (EMCS) instead.

Two experts did not have any experience in the design phase and were not able to consult the appropriate personnel during the telephone conversation time period.

One expert had little experience in the design phase, but remembered no problems applying the Panel design to the HVAC application.

One expert favored design of control systems which included an Air Force Standard Panel over other control schemes because of the availability of the Standard HVAC Technical Specifications. Additionally, because the Panel incorporates a single loop concept, it is easier for the designer to understand due to its similarity to pneumatic controls. However, the maintenance and diagnostic features are difficult for many designers because the features are new concepts.

Round Two Responses. One expert

> ...does not believe `standard specifications' are the way to go. A standard spec will always be a compromise in performance. Every building is different and requires specific solutions not compromises. My experience has shown that the initial cost of the CERL Panel is about 50% more expensive to install than equivalent pneumatic systems. The new trend toward PLC's will result in a cost difference of 100% to 200% over a conventional pneumatic system. A shorter life expectancy and increased maintenance and training will make this Panel even less cost effective.

One expert had no additional comments.

Two experts had no input during the design phase. For one of these experts, the HVAC Control Panel was selected to test the Panel for future HVAC projects. The Control Panel replaced a multizone control system.

One expert's

> ...biggest problem encountered in the design of the retrofit analog HW system...was the lack of accurate documentation on the existing system. The Design Instructions and Technical Specifications provided good guidance leading to a complete design package. The only problem, that I recall, with the standard guidance was that system interlock (HW system on/off relay and HW valve automatic shutoff E-to-P switch) hardware was not included in the control panel. The panel replaced a built-up pneumatic control system. No other option was considered.

To another expert,

> Several problems exist in the design plans:
>
> 1. The technical specifications were never completed into a Guide Specification by detailed examination and wording. It is not clear in the Technical Specification that DDC is not allowed. The definition of "industrial grade components" is not clear, thus the specifications are open to interpretation.
> 2. The sequence for cascading control on heating/cooling systems allows for wasted energy by overlapping temperature ranges.
> 3. Air handling units are shown with cooling coils ahead of heating coils which would cause nuisance low limit alarm and possible freezing.
> 4. No sequence exists for supply fan/return fan matching of VAV system--a necessary design in some applications. Consequently, design engineers believe that they "must" deviate from the Technical Specs to provide a fully workable system. The concept of standardization is lost.

Round Three Responses. Addressing paragraph three in the round one responses, one expert said,

> I do not agree that a performance specification would yield a better product in a government

environment unless there is a mechanism to verify both short term and long term performance. This mechanism does not presently exist nor do I see the potential for it being developed due to resource constraints. A performance spec would yield control systems that are complicated and difficult to maintain. I believe that simple, reliable, standardized control hardware and strategies stand the greatest chance of success.

Addressing paragraph four, the same expert said,

I don't believe that many if any of the present panel functions could effectively be performed by EMCS because I think EMCSs are too complicated. They tend to provide more functions and features than are necessary to save energy.

Addressing paragraph one, round two, the expert said,

Although there may be a compromise in performance due to a standard specification I believe that the long term benefit of improved O&M due to user familiarity with standard control systems will more than offset the initial compromise. As for the initial cost of the hardware and installation, I believe that installation of a factory manufactured control panel can, when mass produced, be much less expensive than the installation cost of a built-up system. I also believe that any electronic or digital system will significantly outperform any pneumatic system. The bottom line comparison to be made here is in labor manhours required to maintain the different types of system. Hardware costs are insignificant compared to labor costs. Given the problems described in ETL 83-1, I believe that there is justification for not placing much emphasis on first cost.

Referring to paragraph five, the same expert said,

I agree that the Tech Specs were never completed into a Guide Specification, it is not clear that DDC is not allowed, and that the definition of `industrial grade components' is not clear. These are all good points. The Guide Specification for HVAC Control Systems being developed by the Army Corps of Engineers addresses and remedies each of these concerns.

Another expert said,

Looking at the control panel from a standardization of controls and drawings aspect, the Air Force training structure has a good chance in building and administrating a training program in preparing base technicians in maintaining HVAC systems. At present the school at Sheppard AFB TX can only teach a few of the numerous types of controls.

AREA 4: INSTALLATION PHASE. During the installation phase, some areas of concern are the ease of installation (mounting and connecting to sensors, controlled devices and EMCS), calibration, training, and documentation. Please relate documentation to installation, calibration, and training where applicable.

Question 5. What were your experiences with the Air Force Standard Panel during the installation of the entire HVAC system? (If this is not applicable to you, please feel free to consult co-workers who may have had more experience. If this is done, please record the individual's name, job title, and experience with the Panel in a format similar to survey question 1. Remember the research is an effort to obtain as much information as possible and disseminate it to all the experts.)

Round One Responses. One expert indicated the Panel is easy to install since only a few wires are required for sensor connection. Training is required for the diagnostics and calibration. If CERL input is used from the Technical Specifications, calibration and operation are simple.

One expert was concerned with the additional cost of the Panel. This expert found a higher first cost for electronic components, such as those in the Panel, as opposed to pneumatic components in a built-up system. This expert estimates a 20-30% cost difference in components alone. This does not include diagnostic features and component housing costs.

One expert encountered no problems during installation and calibration <u>after</u> an explanation of the function of each component was given to the individuals calibrating the system. However, if explanations were not given, the Panel has an intimidation factor which may inhibit proper installation and calibration.

One expert encountered no problems during Panel installation.

One expert was not involved in Panel installation and was not able to consult those involved in the telephone conversation time period.

One expert found "real smooth" installations.

One expert found the installation and calibration procedures too complicated for technicians to understand. This expert believes more training in electronic areas is required for these technicians.

One expert found incorrect installation procedures and calibration at a particular location. This system did not function properly due primarily to the installation of sensors which were incompatible with the Panel controllers, improper design which allowed for a variation in component installation, components outside the Panel being incorrectly connected and controllers calibrated with too narrow proportional band settings. Round Two Responses. Two experts had no problems with installation and calibration.

One expert had the following comments:

> In general, the installation of the panels at the job site is not a complicated procedure. It only requires hanging the panel on a wall and terminating the field wiring and pneumatic tubing to the control panel. If the original step-by-step commissioning instructions are followed the whole installation phase is simplified.
>
> The key to proper installation is proper planning and coordination before the panel is manufactured and sent to the job site. Any `Shortcuts' in the design phase will create corresponding problems in the field. If the controls contractor `educates' himself on what the standard panels should provide the Air Force in terms of simplified installation and maintenance prior to turning the project over to the Air Force, then the quality of training provided to the end user will be enhanced.

Another expert said,

> The analog HW control panel installation and commissioning that I was directly involved with was straightforward. This can be attributed to the panel being factory tested and calibrated and the commissioning procedures were well-documented.

One expert was not involved in the installation phase. The Panel was installed by contract under an MCP project involving the B-1B bomber beddown.

To one expert,

> The `Standard Panel' does not set up clean with non-standard HVAC equipment and non-standard real life requirements going on in every building. Since the CERL Panel is only encountered with the military, contractors will be in a constant state of training and re-training as their people are moved within a company. People will have to be trained and on staff just to do government work. This additional training and staffing will be almost impossible to provide in remote areas.

Round Three Responses. Addressing the last paragraph in round two responses, this expert said,

> A good point is made here, but we must consider the alternative. Military personnel encounter a variety of different types of hardware in their day-to-day O&M activities. To provide adequate training on all varieties of hardware to these individuals is nearly impossible. Couple this problem with low staffing levels and routine personnel turnover and it becomes apparent why government facilities have extensive HVAC control problems.

Another expert said, "The installation is real easy and can be accomplished with in-house maintenance personnel."

AREA 5: OPERATIONS AND MAINTENANCE. Maintenance of the entire HVAC system, including the controls portion, is a major concern of the Air Force. Two important aspects of maintainability include (1) an ability to diagnose the HVAC system from the controls and (2) the reliability of the components of the control system themselves. Diagnostic capability includes the intimidation factor versus the Panel's "seductiveness" to be used by the technician. Long-term reliability is difficult to assess since the Panel has only been mandatory since July 1987, but please relay whatever information you have, including frequency of replacement and/or repair of components and frequency of calibration.

Question 6. What were your experiences with the operations and maintenance of the Air Force Standard Panel? Please state, when making subjective statements, if the judgment is relative to pneumatic, electronic, DDC systems, or an ideal system which is yet to be developed or implemented. (If this is not applicable to you, please feel free to consult co-workers who may have had more experience. If this is done, please record the individual's name, job title, and experience with the Panel in a format similar to survey question 1. Remember, the research is an effort to obtain as much information as possible and disseminate it to all the experts.)

Round One Responses. Concerning maintenance, one expert indicated one Panel had trouble with two electronic-to-pneumatic (E/P) transducers and one reset module. However, no controllers required replacement. This expert also found 75-80% of the technicians were afraid to become familiar with the knobs and buttons composing the Panel's diagnostic features. Once these features had been explained to them, the fear of touching the Panel dissipated.

One expert believes many of the Panel functions could be performed by EMCS. This expert also believes the Panels are too complicated for many technicians and the Air Force training is not sufficient for the complication level as compared to pneumatic controls. The gauges are not used because the technicians do not understand their functions. Instead, technicians are used to tweaking components in an effort to solve a problem, not analyzing it using diagnostics. Training is difficult at base level, especially on bases which use the zone concept. Although the Panels are too complicated, this expert believes standardization is a step in the right direction.

One expert cited a situation during which the Panel was used to expose deficiencies in an HVAC system.

One expert believes the hidden costs in electronic components are due to the inability of the technicians to properly troubleshoot and calibrate electronic systems. This inability, coupled with the problems with electronic components due to heat generation, results in a shorter life for electronic components (12-15 years) compared to pneumatic components (20-22 years). This expert believes if technicians familiar with only pneumatic systems are expected to work with the electronic components in the Panel without proper training, damaged or bypassed components will result. This expert believes the hybrid (electronic controllers and sensors with pneumatic actuators) system mandated by ETL 83-1, Change 1, is a step in the right direction, but more training is required and it may necessitate hiring technicians with a higher level of education. Additionally, this expert is not convinced the Air Force receives the hybrid system it asks for in every case.

One expert believes less maintenance trouble and customer complaints result from the Panel than from built-up or separate component systems.

One expert found many problems with controllers in two different types of Panels. Once the controllers were replaced, no further problems were experienced.

Two experts found no problems with their Panels' operation to date.

Round Two Responses. Two experts had no problems with operations and maintenance. The experts found that the Panels never need adjustment or calibration.

One expert does not have any changes to the above comments. He would like to add, however, that

> Most bases do not have the level of personnel required to properly maintain these panels. Many bases can't currently handle EMCS maintenance, let alone the CERL panel. The Zone Maintenance concept will make the situation even more impossible.

For one expert,

> The control system consists of a single zone system with a controller sensing return air to control the heating and cooling valves. The mixed air dampers are controlled by a comparator economizer which compares the outside air and return air. The system is fairly simple and practical.
>
> We have had to replace the temperature controller, the comparator and several indication meters even though the system had been in operation for only six months. This indicates a high failure rate for the electronic components.

One expert had the following comments:

> To achieve the full potential of the Standard Control Panels in terms of simplified operation and maintenance, a commitment must be made by the Air Force to enforce the specifications. Any shortcuts by contractors defeat the intent of a standard program.
>
> 1. Standard Design: Allows training of personnel for one application regardless of where they are stationed or transferred.
>
> 2. Standard Maintenance Instructions: Allows step-by-step troubleshooting of the system with both cause and effect explained for each step, i.e., what

should be indicated by the diagnostics and what is causing the problem if improper indication is discovered.

3. Standard Diagnostics: Once a person has been trained on a single panel, the familiar diagnostics on future panels are no longer intimidating.

4. Standard Equipment: Allows maintenance personnel to be trained on generic electronic controls. There is no requirement for vendor specific training at each base as is required by DDC. Each of these items has been documented in detail in the Design Instructions and Technical Specifications.

One expert said,

> The analog HW control panel from one manufacturer (Manufacturer A)...experienced repeated problems with the HW reset controller. This panel was eventually replaced with another manufacturer's HW control panel (Manufacturer B). This decision was made because, in a separate application, Manufacturer B's HW control panel had been working very well without any problems for about 2 years.
>
> Additionally, laboratory performance testing of standard analog panels 1, 3, 4, and 8 showed that each performed as expected with the exception only of one manufacturer's FSC static pressure control panel. This panel's soft start feature did not work properly.

Round Three Responses. Referring to the second paragraph of the round one responses, one expert said,

> I believe that diagnostic features are valuable. Typical HVAC control systems have few if any diagnostic features. This has become the norm. As a result, technicians are more accustomed to tweaking than diagnosing. Given the availability of diagnostic features, I believe they will eventually catch on and prove to be useful.

Addressing the fourth paragraph, the same expert said,

> While it may be true that electronic components have a shorter life than pneumatic components, electronic components maintain calibration much longer.
>
> Although a high level of education may be needed to effectively work with the panels, I believe that due to standardization the learning curve can be shortened because systems designed by different A/Es and installed by different contractors will be similar.

Addressing the round two responses, paragraph two, this expert said,

> Although the analog panel may present some maintenance difficulties, I believe that, over time, maintenance staff abilities to maintain the analog panel will improve as more panels are installed and familiarity increases. I don't believe a similar trend is possible without standardization.

Another expert said,

> One problem with the panel is that the Air Force did not sell the panel to the users and the construction agents. The panels were almost forced upon them. This opposition to the panel has caused a reluctance to install them and learn how to operate and maintain them. As far as the panel itself, it is very easy to learn and maintain.

AREA 6: FUTURE USE.

Question 7. Considering all the pros and cons of your Air Force Standard Panel installation, would you install another one? Why or why not?

Round One Responses. This question was not asked during the first round of the survey, hence, no responses are provided.

Round Two Responses. One expert said yes, he would install other Panels. However, the Control Panels installed at this location do not have controls parts which are readily available. Therefore, a different brand would be requested.

One expert said,

> Due to the time lag for their construction between mandating design and system acceptance, too few systems have been installed to determine overall effectiveness of the program, but we believe program and system to be sound. It would seem appropriate to evaluate and revise the Technical Specifications to get `bugs' out

but maintain the program. Obviously, standardization implies a long-term commitment.

Another expert said that the manual adjust set-up is great for the technicians to use in testing and calibrating the system. Overall, provided there was a debugging of the electronic components, they would like to have more Panels installed due to the ease of maintenance.

One expert responded, "Yes. Only if required to by the spec."

One expert had no comments.

One expert said,

> I prefer the Standard Panel over DDC or pneumatics in government applications, but it is a bit outdated. The Army's new Single-Loop Digital Control (SLDC) Panel has been designed to overcome several of the drawbacks of the Analog Panel. I prefer the SLDC Panel over the Analog Panel.

Round Three Responses. One expert said,

> Since the Army Corps of Engineers have developed a new standard control panel that uses DDC type controllers and they also have standard HVAC system drawings, I would recommend that the Air Force discontinue the original panel and move to adopt the Army's new panel.

AREA 7: ADDITIONAL COMMENTS Please provide any additional comments you may have about either the Air Force Standard Control Panel or the Delphi technique employed to solicit and consolidate expert opinions. Include, if possible, other sources of potential experts in this area. These individuals may be included in the final (third) round of this survey or be provided as sources for future research in this area.

Round One Responses. One expert mentioned work done by the US Navy using control systems composed of DDC boards. The primary problem with these systems was the inability of DDC controls to talk to each other due to the lack of a common language.

Four experts were not able to make further comments during the telephone conversation time period.

One expert mentioned the possible replacement of the single loop analog controllers with single loop microprocessors. This expert believes that, due to the advantage of microprocessors in space, i.e., only one Panel required to house many controller functions, microprocessors are the wave of the future in Standard Panels.

One expert wishes the Air Force had more Panels installed because the Panels are so simple to maintain, have good control, and don't require the technicians to know so many systems.

One expert predicts a company will be able to make the Panel very cheaply and underbid the "good" companies for business. When this happens, the Air Force will end up with junk. To avoid this, the expert suggests the Air Force write a super performance specification.

Round Two Responses. Four experts had no additional comments.

One expert said,

> The SLDC Panel being developed by the Army is based on the same concepts, but has several advantages over the analog control panels. It is less expensive

> to apply because there is only one panel versus 8. Also, it provides more elements of standardization including interchangeable controllers, ease of EMCS interface, a back panel which allows for standardized wiring and standard rail mounted devices.
>
> The SLDCs are state-of-the-art digital controllers which are readily available and fully interchangeable not only between different control applications (PID, setpoint reset, dual input, and economizer), but can also be interchanged with a different manufacturer's controller because standard 4-20 mA I/O signals provide more features at less cost than the industrial grade analog controllers. Each SLDC can display its own process whereby the maintenance person can manually modulate the end-device. These features eliminate the need for most of the diagnostic features (knobs, buttons, and displays) presently available with the analog panel. In addition, most SLDCs have a self-tune feature which greatly simplifies the commissioning procedure.

One expert said that one advantage in using the Standard Control Panel is the training of the base maintenance personnel in a select type of controls and control strategy.

Round Three Responses. One expert said,

> I maintain that any standardization is to the benefit of the Air Force as far as being able to train base maintenance personnel in maintaining HVAC systems. The bottom line is that if the base maintenance person does not understand the controls and HVAC system design intent then the maintenance person is going to disconnect the controls and re-design or re-configure them to a point that they can manipulate the system to perform as they understand it. In most cases this is not to the advantage of the Air Force or building occupants.

<u>Summary</u>

The past chapter presented a great deal of data collected via various means including a qualitative analysis of installation, calibration and operating procedures, a qualitative and quantitative comparison of data collected from the mixed air and supply air controllers for each system, and a presentation of data collected through three rounds of a Delphi survey. It is believed that the comparison of the Standard Panel against the built-up system was thorough and definite conclusions can be reached which are externally valid. The presentation of these conclusions, and recommendations for future research, will be presented in Chapter 5.

V. Conclusions and Recommendations

Chapter Overview

The past four chapters presented research designed to determine if the Air Force Standard Control Panel would aid in solving the Air Force's problems with complicated and unreliable Heating, Ventilating, and Air Conditioning (HVAC) controls. The investigative questions which guided this research were the following: 1) How do the time required for and the difficulty level of design and installation of the Standard Panel compare with other controls systems? 2) How does the ability to maintain setpoint compare between the Panel and other systems? 3) How does the standard format of the Panel impact the ability of the technician to diagnose the HVAC system? 4) How does this diagnostics capability compare with the ability of a technician to diagnose via other systems?

To answer these questions, the researcher chose to conduct an experiment and a Delphi survey of experts from the controls field who were familiar with the Standard Control Panel. The null hypothesis for this research was the following:

> The difference between the Air Force Standard Control Panel and other control systems in terms of ease of design and installation, ability to control in the intended manner, and reliability as measured by

drift from setpoint is not significant enough to warrant mandated use of the panel.

The alternate hypothesis for this research was the following:

> The difference between the Air Force Standard Control Panel and other control systems in terms of ease of design and installation, ability to control in the intended manner, and reliability as measured by drift from setpoint is significant enough to warrant mandated use of the panel.

This chapter draws together all the information in Chapters 1-4. The format consists of seven sections following this Chapter Overview. The first four sections correspond directly with each of the four investigative questions. Within each investigative question section, the researcher attempts to answer the question drawing on data from each type of research: the qualitative analysis of the installation, calibration and operation procedures and the qualitative and quantitative analysis of the statistical portions of the experiment, and the relevant data from the Delphi responses. The fifth section supports or fails to support the null hypothesis. The sixth section contains recommended changes to the Standard Panel and the Standardized HVAC Technical Specifications and recommendations for future research in this area. The seventh section includes additional comments by the researcher.

Research Question 1

How do the time required for and the difficulty level of design and installation of the Standard Panel compare with other controls systems?

Experiment. First, design from a retrofit perspective is presented as observed by the researcher during the "Installation, Calibration and Operation" portion of the experiment. Calibration is considered part of installation. Both the built-up system and the Standard Control Panel system were designed as they were installed. It is difficult, if not impossible, to separate the thoughts associated with design from those associated with installation. Therefore, the advantages and disadvantages of each system will be described as a single comparative process.

The built-up system required approximately 100 hours to design, install and calibrate. The reader is reminded that the built-up system included static pressure, hot water, mixed air and supply air control, as compared to the Standard Panel, which included only supply and mixed air control. The difficulties encountered in designing and installing the built-up system include relationships and compatibility between components, and the detail required since each desired function must be designed and a component procured for it.

The Standard Panel system required approximately 127 hours to design and install. Over 70% of this time was required for calibration. This excessive amount of time was not due to any fault in the Panel, but to the lack of positive positioners on the damper actuators. On one hand, it is somewhat irrelevant where the fault lies since the built-up system also interacted with the same controlled devices. On the other hand, most of the time required was due to the integral portion of the controller, a feature the built-up system mixed air controller did not have. Nonetheless, in comparing the systems, the amount of time required to find the workable solution was noteworthy.

The remainder of the time spent on design and installation of the Standard Panel (30 hours) was considerably less than that required for the built-up system. Although the panel was only controlling mixed air and supply air, more time was required for diagnostic features such as position potentiometers and new sensors, which were not included or required in the built-up system.

Delphi. The Delphi survey questions addressing this research question did not distinguish between retrofit and new systems. It was, however, divided between design and installation of the Standard Panel compared to other control systems.

Comparing first the relative ease of design, the experts were divided. Two of the experts favored the Standard Panel system of design. Among the reasons cited for their opinions were that the Panel design is on AutoCAD computer assisted design software package, similarity of single loop controllers with pneumatic controls, greater ability to train controls specialists, and the availability of the Standard HVAC Technical Specifications. This combination of reasons facilitates design.

Four experts did not favor the Standard Panel system of design. Among the reasons cited were the compromises required for any standard specifications, additional first cost, problems with the Technical Specifications, and the reluctance of design engineers to sign off on a design which is not truly their own.

Two of the experts did not have experience with the Panel during the design phase.

Regarding the comparative ease of installation, five of the experts found either "real smooth" installations or "no problems." Their reasons for these opinions were the simplicity of wire and pneumatic tubing connections and the factory tested components of the Panel. Two of these experts did mention the necessity of complete and thorough explanations to the technicians of the function of each component.

Two of the experts found or anticipated problems with the Standard Panel installation. One cited additional cost of the Panel and the difficulty of trying to match Standard Panels with non-standard HVAC requirements, one believed the procedures were too complicated for technicians to understand, and one found an incorrect installation completed by a contractor.

One of the experts had no experience with the Panel during installation.

To summarize and attempt to answer the investigative question, the data found by the researcher in the experiment and the Delphi survey indicate no clear superiority of the Panel over other forms of control systems in terms of design and installation.

Research Question 2

How does the ability to maintain setpoint compare between the Panel and other systems?

Experiment. Relevant data from the experiment in this discussion includes the overall operability of each system, the comparative drift rates of each system's mixed air and supply air controllers, and the statistical comparison of the same controllers. While operating the Standard Panel system, some problems arose. The first of these involved the lack of positive positioners on the damper actuators and resulted in the Panel system tripping the freezestat. While this is not strictly the fault of the Panel, the fact that its effects are considerable -- shutting down the entire air handling system -- and the fact that the built-up system did not trip the freezstat while using the same controlled devices, make the point noteworthy. Another point concerns the economizer settings and the additional load on the cooling coils and the additional heat and humidity in the space resulting from the settings.

The remainder of the problems arising from each system's control result from the controlling logic discussed in the operation section of Chapter 4. The Standard Panel logic caused the space to become too cool (67oF) on a few occasions (see Table 15). But, a majority of the time, the temperatures in the space were between 68-72oF. Additionally, the minimum outside air setting reduced stuffiness for the space occupants.

On the other hand, the space temperatures were frequently hot when controlled by the built-up system (see Table 16). The researcher witnessed only one occasion when the mixed air controller actually regulated the mixed air temperature between January and March 1989. While this may mean that the logic designed into the built-up system worked properly and the load on the heating system was not as great as with Standard Panel control, it also meant that this one occasion was the only time the space occupants received fresh air through the air handling system. On all other occasions, the system violated minimum outside air percentages required by AFR 88-15 (Department of the Air Force, 1986:15-54).

Statistically, each system's ability to maintain setpoint was determined using two methods -- drift analysis and drift comparison of each system's mixed air and supply air controllers.

From the drift analysis, none of the values obtained were statistically significant except for the drift of the Standard Panel's supply air controller, which was .0097°F/week. At this rate, the supply air controller would not be 10°F out of calibration and therefore require recalibration for approximately 10,000 weeks. While this figure may seem outrageous in that the drift may not be linear over time, it is nonetheless a tribute to the system's effectiveness.

The Panel's mixed air controller, and the built-up system's mixed air and supply air controller's ability to maintain setpoint are also commendable. The lack of statistically significant drift indicates that the drift measurements recorded by the researcher can not be attributed with certainty to any identifiable cause.

The reader is also reminded, however, of the limitations discussed in Chapter 4. Specifically, these limitations included the length of time the data was collected, use of actual controller input values instead of artificial values, and the accuracy of the measuring instruments.

Additionally, no definite conclusions can be drawn from the drift comparison. None of the Beta3 -- the Panel's contribution to system drift -- values were statistically significant. Since the same data was used for the drift analysis as was used for the comparison, the reader is again reminded of the data limitations.

Delphi. Concerning operations and maintenance, six of the experts favored the Panel's record while two did not. Some of the reasons cited for the Panel included its ability to diagnose problems and less trouble and fewer customer complaints as compared to built-up systems. Only two of these experts actually found no problems. The other four incurred controller and transducer malfunction and technician hesitancy, but did not indicate that the overall problem was more severe than with other control systems. Additionally, these four experts mentioned that, after the initial bugs were worked out, no further problems were encountered.

Two of the experts did not believe the Panel's operation and maintenance record rivaled other control systems. Both of these experts thought the Panel was too complicated for the technicians to understand. One of them also thought the cost was too high and electronic components were inferior to pneumatic components. The other believed many of the functions performed by the Panel could be done by an EMCS.

To summarize, although the data collected over 29 weeks by the researcher did not indicate any clear superiority of one control system over the other, a majority (75%) of the experts reported favorable operations and maintenance records of the Panel as compared to other control systems.

<u>Research Question 3</u>

How does the standard format of the Panel impact the ability of the technician to diagnose the HVAC system?

<u>Experiment</u>. During the experiment, there were three particular situations in which the diagnostic features of the Standard Panel were particularly helpful in diagnosing the HVAC system. The first of these was the discovery of the screw in the outside air damper. This screw locked the louvers of the damper in place and did not allow any outside air into the system and was discovered by comparing outside air, return air and mixed air temperatures.

The second instance was in the determination that the cooling coils were not functioning properly. This was discovered by comparing the air temperatures of the mixed and supply air sections of the air handling unit. The problem was eventually traced back to the compressor, which was cutting out due to low pressure.

The third situation was more continual. The researcher collected data on the HVAC system via the Panel on a weekly basis. This data collection process took approximately 5 minutes if the Panel was in control and approximately 15 minutes if the Panel was not in control. The additional 10 minutes was due to the settling time for the supply air and mixed air controllers. Since the values collected were already in familiar terms, immediate system analysis could be performed and any problem could be isolated.

Delphi. No specific question was asked of the experts concerning the Panel diagnostics, yet many times the subject arose in the responses. One of the experts was against the diagnostic features in the Panel. He said the features were too complicated and recommended the functions be performed by EMCS instead.

Four of the experts favored the diagnostics but two of these recommended training for the technicians to enable them to properly use the features. If there was no training, problems would arise. Among the reasons cited for liking the diagnostics were the ease with which the technicians can understand the HVAC system and the Control Panel and the ability to quickly isolate problems. One of these experts did mention the difficulty some design engineers would have with the diagnostics because it was a new concept.

Three of the experts did not mention the Panel's diagnostic capability.

To summarize, although one of the experts do not favor the diagnostics in the Panel, the researcher and four of the experts believe diagnostic features provide a significant contribution to the technician's ability to understand and troubleshoot the HVAC system and the controls.

Research Question 4

How does this diagnostics capability compare with the ability of a technician to diagnose via other systems?

Experiment. Using the three situations discussed in the previous section, the researcher can compare the ability to diagnose using the Standard Panel with diagnosing using the built-up system. Although the built-up system was fully operational before the Standard Panel, the first two problems -- screw in the damper and cooling system malfunction -- were not discovered through the built-up system. The researcher believes the reasons for this are the values obtained through the built-up system are pressures which must be converted to temperatures for the particular areas. While this process is not difficult (see tables 27 and 29), it requires particular knowledge of the system's sensor ranges, proportional bands and percent authority and an ability to manually control output pressures. On he other hand, the Panel's diagnostic values are instantaneous and readily familiar in degrees Fahrenheit, position indicators are displayed on meters, and controlling output pressures requires only pressing a button and turning a knob. All these features make isolating problems infinitely easier.

The third situation -- weekly data collection -- was also much easier with the Panel than with the built-up system. As mentioned earlier, the data collection process for the Panel required between five and fifteen minutes depending on control, and was already in familiar units. On the other hand, the built-up system required 30 minutes, regardless of control, because the act of reading the pressure through the input port destabilized the controller. The researcher then had to wait until the controller output was stable before reading that value. Additionally, the pressures required conversion into understandable temperature units.

Delphi. No direct comparisons were made between the diagnostics of the Panel and diagnostic features of any other control system either in questions or within the responses of the experts.

To summarize, due to the quickness and ease with which the technician can understand the values, the researcher believes the diagnostic features of the Standard Panel were far superior to the built-up system.

Null Hypothesis

As a reminder, the null hypothesis for this research was the following:

> The difference between the Air Force Standard

Control Panel and other control systems in terms of ease of design and installation, ability to control in the intended manner, and reliability as measured by drift from setpoint is not significant enough to warrant mandated use of the panel.

The alternate hypothesis for this research was the following:

> The difference between the Air Force Standard Control Panel and other control systems in terms of ease of design and installation, ability to control in the intended manner, and reliability as measured by drift from setpoint is significant enough to warrant mandated use of the panel.

Summarizing the previous four sections, the Standard Panel was not superior to other control systems in terms of design and installation and was not statistically superior in terms of ability to maintain setpoint using experimental data. But when the overall operability of each experimental control system was considered and the opinions of the Delphi experts included, the Panel was believed to be superior in terms of ability to maintain setpoint and diagnostics capability. Based on this data, the researcher is required to reject the null in favor of the alternate that the Standard Panel is superior enough to other control systems to warrant mandatory use.

Recommendations

The researcher recommends the following improvements be made to the Panel and the Standardized HVAC Control Specifications:

1) Follow-up calibration should be required during different seasonal temperatures to ensure system functionability. Instructions should also consider the impact on the system response of the lack of positive positioners on the damper actuators.

2) Economizer differential should be variable to consider effects of humidity in the outside air on the cooling system.

3) Extensive training should be conducted to overcome initial fears of the Panel and to ensure technicians and engineers are fully knowledgeable of the Panel's capabilities and operations.

4) Specifications must be enforced to achieve true standardization.

5) Labelling should be required for all wire and pneumatic tubing connections on the Panel.

6) Control strategies used in the Panel should be reviewed thoroughly. Particularly, some means of resetting the supply and mixed air setpoints based on return air temperature should be considered so the HVAC system does not provide 55oF air to a 60oF space.

The recommendations for future research concerning the Panel can be focused in two directions. The first direction can be continued research involving the analog Standard Panel with particular emphasis on those portions of this research where there was no superiority of the Panel over any other control system. Specifically, those areas were statistical drift analysis and comparison and the design and installation phase.

The second direction involves the new microprocessor based Standard Panel developed by the Army. While this Panel is purported by three Delphi experts to have many advantages over the analog Panel, no definite research has been done in this area. Therefore, disadvantages may exist as well.

Additional Comments

Considering all the information gathered in the course of this research, the researcher feels compelled to discuss the impact of the information on the Civil Engineering community and the Air Force as a whole.

Clearly, the necessity for accurate and reliable control systems exists. Users of HVAC systems -- customers of CE -- depend on the system providing a comfortable working environment on a daily basis. When the system fails, not only is energy wasted but productivity is lost as well. In an atmosphere of rising costs, budget cuts, and manpower shortages, neither wasted energy nor lost productivity is acceptable.

Attempts thus far to consistently maintain a proper environment for the customer have failed. One of the major causes has been a lack of standardization of control systems. When different designers create their own particular systems, the HVAC system may function well for a period of time. But when it fails, no one can fault another engineer or technician if he or she cannot understand this particular control strategy in a field of hundreds and chooses to tear it out and replace it with something he or she does understand or bypass particular portions rather than work within the confines of the first designer's mind. The fault lies not with the designer or repair person but with the requirements placed on both positions and the unstructured framework given to the individuals in which to meet those requirements.

This realization led to the development and mandatory use of the Air Force Standard Control Panel. This research found the Panel to be superior enough to other control systems to warrant mandatory use. But, the researcher foresees obstacles in implementing the Panel in the field. One of these obstacles will be cost. The first cost of the Panel is considerably higher than other control systems. Additionally, it is difficult to calculate life-cycle costs when the Panels have been required for only two years.

Based on the experimental findings of the researcher and the opinions of the experts, the researcher believes the Panel falls in the same category as computers. Although initially attempts were made to justify computers based on dollars saved, eventually computers were simply accepted as a necessary part of raising the effectiveness and efficiency level of the organization to a new plateau. Now, it is difficult to imagine an aspect of life not affected by computers.

This researcher believes the same will occur with the Standard Panel. It may not be the same Panel used in this research, but some form of Panel will become commonplace in mechanical rooms simply out of necessity. Engineers and technicians can no longer be expected to know every control strategy in existence. By the same token, the Air Force can no longer be expected to fund complete control system retrofits every time a new technician attempts to repair an HVAC problem. So although first cost may initially be an obstacle, eventually the requirement to provide a productive environment for the customer will overcome this obstacle.

When first cost is accepted, other obstacles expressed by particular experts will also be overcome. Designers will become familiar with using the Panel in their HVAC systems, technicians will become comfortable with the diagnostics, and replacement parts will become readily available. To reach that point, however, more research may be required, perhaps with the new microprocessor-based Panel, and more training is necessary, to overcome the small obstacles which can prevent the Panel's acceptance the same way fear delayed acceptance of the computer. The outcome is inevitable. The amount of benefits enjoyed by Civil Engineering and the Air Force depends on how fast the outcome is reached.

Appendix A: Air Force Standard Panel Installation Instructions

Commissioning Instructions for the VAV Temperature Control Panel

The VAV temperature control panel modulates the chilled water coil and the outdoor and return air dampers to maintain the desired discharge air temperature leaving the fan system.

Step 1. Adjust pilot positioners.

Before adjusting the VAV temperature control panel, check to be sure that the pilot positioners on the chilled water valve and on the outdoor/return air dampers are set to operate between 3.5 and 14.5 PSIG$\pm$1/2 PSIG.

Step 2. Adjust proportional band and reset rate.

Remove the covers from DAMPER CONTROLLER C2 and COOLING CONTROLLER C1 and set the proportional band on each to 10 percent corresponding to a 10°F proportional throttling range. Set the integral reset rate, Tn, to 60 seconds on the DAMPER CONTROLLER C2 and to 120 seconds on the COOLING COIL CONTROLLER C1.

Step 3. Adjust setpoint of COOLING COIL CONTROLLER.

Turn the meter select switch to C1 SET and adjust the setpoint of the COOLING COIL CONTROLLER C1 to the specified delivery air temperature.

Step 4. Adjust setpoint of damper controller.

With the fan running, turn the timer past 5 minutes, turn the COOLING COIL MANUAL ADJUST knob and the DAMPER MANUAL ADJUST KNOB fully counterclockwise and press the SET button on the COOLING MANUAL ENABLE and DAMPER MANUAL ENABLE to put the system under manual control and cause the cooling coil valve to close, the outdoor damper to close, and return air damper to open. Allow the system to stabilize. Turn the meter select switch to C1 TEMP (the fan discharging temperature) and then to C2 TEMP (the mixed air temperature). C1 TEMP should be higher than C2 TEMP because of the heat added to the air stream by the fan. Once the temperature rise across the fan has been determined, turn the selector switch to C2 SET and adjust the set point of the DAMPER CONTROLLER C2 to the desired temperature minus the temperature rise across the fan. Return the fan system to automatic control by pressing the RESET button for both the dampers and the cooling coil.

Step 5. Adjust minimum damper position.

Next adjust the minimum position for the outdoor/return air dampers. It is first necessary to compute the desired mixed air temperature that corresponds to the proper proportion of outdoor and return air. The calculation is as follows:

$$\text{Mixed air temp} = (F)OA + (1-F)RA$$

where F = the specified outdoor air fraction
OA = outdoor air temperature
RA = return air temperature

For example, if the desired minimum outdoor air is 20 percent, then F = 0.2. If RA = 68°F and OA = 50°F then:

$$\text{Mixed air temp} = .2 \times 50 + (1-.2) \times 68 = 64.4^\circ F$$

Next push the DAMPERS MINIMUM POSITION SET button. While holding the button down, unlock and adjust the DAMPERS MINIMUM POSITION SET knob slowly until the desired mixed air temperature is achieved (set meter select knob to C2 TEMP to observe the mixed air temperature). Note that the adjustment of the minimum outdoor damper setting is best accomplished when the outside air temperature is considerably hotter or considerably colder than the return air temperature. Furthermore, if excess amounts of outdoor air are indicated by the mixed air temperature when the damper minimum position setting switch is at 0, excessive damper leakage is indicated and actuators, damper blades, and linkages should be checked to be sure that they are operating properly. On the other hand, damper leakage alone is usually enough to satisfy outdoor air requirements of 10-20%.

Step 6. Check stability.

It is necessary to check to be sure that the controllers C1 and C2 are adjusted properly to provide stable operation. For the DAMPER CONTROLLER C2, stability checks are best made during cold weather when a small change in damper position results in a large change in mixed air temperature. To check for stability, set the meter select switch to C2 SET and suddenly change the set point of controller C2 to cause a 5-6°F change in the controller set point. Turn the meter select switch to C2 TEMP and observe the meter, the pressure showing the pneumatic output to the dampers, and the OA and RA DAMPER POSITION indicators as the controller attempts to bring the mixed air temperature to its new set point. If the mixed air temperature reaches its new set point within 2-3 minutes and without excessive oscillation or hunting, then the proportional band setting, Xp, and the integral reset rate setting, Tn, are approximately correct. If excessive hunting or oscillation is observed, then the proportional band is too narrow and Xp should be adjusted to larger values until the hunting or oscillation stops. Note that the period of oscillation or hunting can be of the order of 3 or 4 minutes, especially under low air flow conditions. Thus it will be necessary to observe the system for 10 to 20 minutes to be sure that oscillation are not occurring. The cooling coil control loop must also be checked to be sure that it is stable. This should be done during weather warm enough to cause the cooling coil to be required but during periods of fairly light load on the coil when the cooling coil valve is not far open. The procedure is the same as in testing the stability of the damper control loop, i.e. set the meter select switch to C1 SET. Suddenly change the set point of the COOLING COIL CONTROLLER C1 by about 5°F. Set the meter select switch to C1 TEMP and observe the coil discharge temperature and output pressure to the coil valve actuator. If excessive oscillation or hunting occurs, adjust the proportional band to a higher value stop oscillations [Chostner, 1987].

SEQUENCE OF OPERATION FOR VAV CONTROL SYSTEM

The VAV heating and air conditioning system has three modes of operation, OFF, NORMAL, and WARM UP. Normal operation is initiated (usually at the beginning of the working day) by a contact closure from a local time switch or a remote energy monitoring and control system. this contact closure provides power to the Hot Water Temperature Control panel and the fan motor starter. Power to the VAV Temperature Control panel, and the VAV static pressure control panel is supplied through auxiliary contacts on the fan motor starter.

At the end of the occupied period, the time switch or energy management control system de-energizes the fan starter relay and Hot Water Temperature control panel interrupting all power to all the control panels.

Discharge and Mixed Air Temperature Control

The cooling coil and outdoor/return air dampers are controlled by a VAV Temperature Control panel.

When power is supplied to the VAV Temperature Control panel, the cooling coil chilled water valve is controlled by electronic PI controller C1 through an electric to pneumatic transducer to maintain a constant discharge temperature.

The mixed air temperature is controlled by electronic PI controller C2 through a comparator relay, a high signal selector and an electronic to pneumatic transducer so that the outdoor and return air dampers are modulated to maintain the desired mixed air temperature so long as the outside air is colder than the return air. The electronic high signal selector compares the voltage from the electronic PI controller with the voltage produced by a minimum positioning adjustment knob. If the output from the electronic PI controller is less than the output from the minimum positioning knob, the minimum positioning signal will control the dampers at their minimum position . When more than minimum outdoor air is needed, the electronic PI signal will be higher than the minimum positioning signal and its value will be used to control the electronic to pneumatic transducer, modulating the outdoor and return air dampers accordingly. Whenever the outdoor air is warmer than the return air, the comparator relay opens, disconnecting the high signal selector. Hence, the highest signal is from the minimum positioning switch and the outside air with dampers return to their minimum position. When the system is off, the outdoor air dampers return to their normally closed position [Chostner, 1987]

MAINTENANCE CHECKLIST FOR VAV TEMPERATURE CONTROL PANEL

CAUTION: When applying the Maintenance Checklist, it is important to remember the VAV Temperature Control Panel is controlling the building HVAC system. Only qualified personnel shall perform the following procedure. Johnson Controls, Inc. shall not be liable for any damages due to misuse, negligence or accident.

1) Check to be sure the POWER ON light is illuminated and that the Supply Air Pressure is 18 to 22 Psi.

2) Set the meter select switch to C1 SET then to C2 TEMP. If the system is being supplied with chilled water and the control system is working, the discharge

air temperature, C1 TEMP, should be very close to its setpoint, C1 SET.

3) Set the meter select switch to OA TEMP (the outdoor air temperature), RA TEMP (the return air temperature), C2 TEMP (the mixed air temperature), and C1 TEMP (the discharge air temperature) in turn to be sure the sensed temperatures are reasonable. C2 TEMP should be between RA TEMP and OA TEMP (even if the outside air dampers are wide open, return air damper leakage is likely to keep C2 TEMP from being exactly the same as OA TEMP). The discharge air temperature, C1 TEMP, may be warmer or cooler than the mixed air temperature, C2 TEMP, depending on whether or not the cooling coil is in operation.

4) If any of the above temperatures seem unreasonable, use the PUSH TO DUE IN TEST RTD buttons and the selector switch to be sure the temperature bridge circuits are functioning. The selector switch should be set to the appropriate TEMP setting while each test button is pushed. For example, the select switch should be on OA TEMP while the OA test button is pushed, on C2 TEMP while the MIXED AIR test button is pushed and so on. The test RTD simulates a temperature of about 100oF, therefore the meter should display a value close to 100 when the test button is pushed. If this value is shown when the test button is pushed but a very large reading appears when the button is released, one or more of the sensor leads are probably disconnected. If this value is very low, a short is indicated.

5) The RA AND OA COMPARATOR ECONOMIZER can also be checked by using the test buttons. Pressing the OA test button simulates a very high outdoor air temperature. With this button pressed, the ECONOMIZER OPERATION PERMITTED light should be off and the dampers should go to the minimum outdoor air position. Pressing the RA test button simulates a very high return air temperature. With this button pressed, the ECONOMIZER OPERATION PERMITTED light should be illuminated and the dampers will be controlled at or above the minimum outdoor air position by DAMPER CONTROL C2.

6) To test the Electronic-to-Pneumatic transducers, turn the timer past 5 and press the SET button on the COOLING COIL MANUAL ENABLE section to the panel, then turn the COOLING COIL MANUAL ADJUST knob back and forth to supply varying voltages to the Electronic-to-Pneumatic transducer. The needle on the OUTPUT TO

COOLING COIL pressure gauge should move back and forth as the knob is turned. The valve and COOLING COIL VALVE POSITION indication meter should also move in response to changing pressure to the valve actuator. Press the RESET button to return the valve to automatic control. Return to automatic control is also achieved when the timer "times out" or is turned to the 0 minutes position. The same procedure should be followed to test the damper Electronic-to-Pneumatic transducer and damper actuators.

7) The minimum damper position can be checked by pushing the PUSH TO TEST DAMPER MINIMUM POSITION test button. This button places the dampers at the minimum outdoor position (nothing happens if the RA AND OA COMPARATOR ECONOMIZER has previously placed the dampers at the minimum position or the output from DAMPER CONTROL C2 is below the minimum position). The DAMPERS MINIMUM POSITION SET knob should not be adjusted except in accordance with the Commissioning Instructions.

8) The output of controller C1 and C2 can also be observed by positioning the selector switch to C1 OUT and C2 OUT respectively. The meter will display the output as a percentage of full scale (full scale is approximately 10 volts). If the coil valve or dampers are in the wide open position, the voltage may be somewhat higher than 100 percent. Note that if the ECONOMIZER OPERATION PERMITTED LIGHT is off, C2 OUT is not the output from controller C2 but is the voltage set by the DAMPERS MINIMUM POSITION SET knob to hold the dampers at the minimum outdoor air position. If the cooling coil and dampers are in the MANUAL mode (see step 6 above), then C1 OUT is percent of full scale voltage produced by the COOLING COIL MANUAL ADJUST knob and C2 OUT is the percent of full scale voltage produced by the DAMPERS MANUAL ADJUST knob.

9) None of the instruments or components in the control panel are intended to be repaired in the field. If the above checks reveal a defective component, it should be replaced [Chostner, 1986].

Appendix B: System Calibration Data

Table 17. Mixed Air Calibration.
(PB = 25, Setpoint = 70, Tn = 60)

Time (minutes)	Vout (% voltage)	MA Temp (oF)
0.0	23.1	68.4
0.5	51.0	72.7
1.0	69.9	71.4
1.5	55.0	68.2
2.0	23.1	66.6
2.5	23.1	68.4
3.0	23.1	70.8
3.5	41.0	72.4
4.0	67.0	72.3
4.5	65.0	69.3
5.0	42.5	67.3
5.5	23.1	67.2
6.0	23.1	69.6
7.0	42.0	72.5
7.5	51.7	72.3
8.0	47.0	69.8
8.5	40.0	68.9
9.0	34.7	68.9
9.5	34.9	69.6
10.0	35.5	70.0
10.5	37.2	70.2
11.0	37.8	70.2
11.5	39.1	70.2
12.0	41.3	70.4
12.5	43.0	70.3
13.0	43.6	70.2
13.5	44.0	70.1
14.0	42.9	69.9
14.5	41.3	69.7
15.0	40.9	69.9
15.5	43.2	70.3
16.0	45.4	70.4
16.5	46.7	70.3
17.0	45.0	69.8
17.5	41.8	69.4
18.0	39.3	69.5
18.5	38.7	69.7
19.0	37.7	69.7
19.5	38.3	70.0
20.0	38.7	70.0
20.5	38.6	70.0

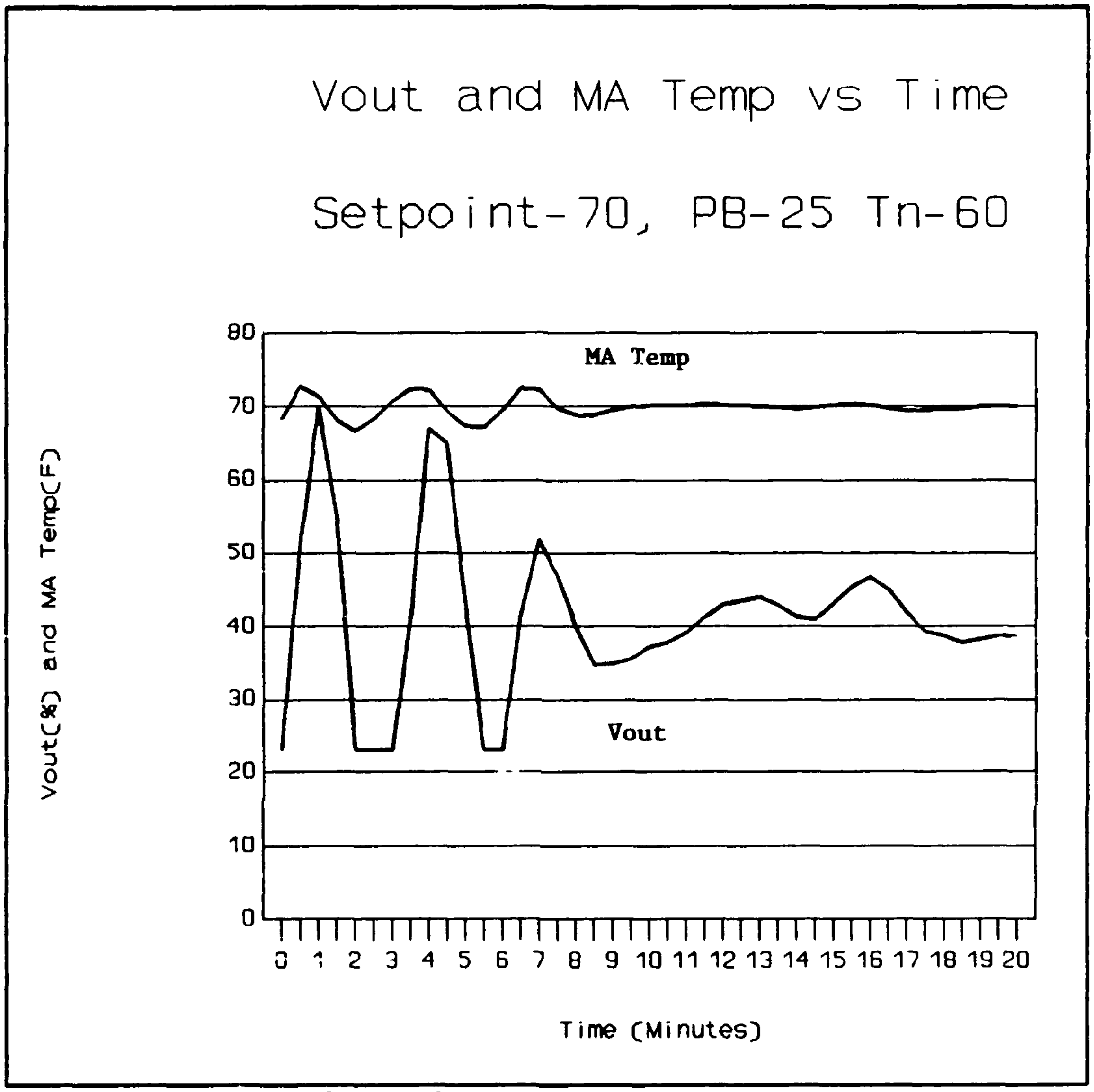


Figure 21. System Response
(Setpoint = 70, PB = 25, Tn = 60)

Table 18. Mixed Air Calibration.
(PB = 25, Setpoint = 64, Tn = 70)

Time (minutes)	Vout (% voltage)	MA Temp (oF)
0.0	23.1	71.6
0.5	25.8	71.8
1.0	65.5	71.6
1.5	74.0	65.5
2.0	42.0	60.5
2.5	23.1	66.0
3.0	23.1	66.0
3.5	60.0	68.5
4.0	67.0	65.6
4.5	47.0	61.6
5.0	20.0	60.1
5.5	21.0	63.7
6.0	64.0	68.0
6.5	67.0	65.3
7.0	40.0	61.1
7.5	16.0	60.3
8.0	30.0	65.4
8.5	66.0	68.3
9.0	65.0	64.5
9.5	36.0	60.0

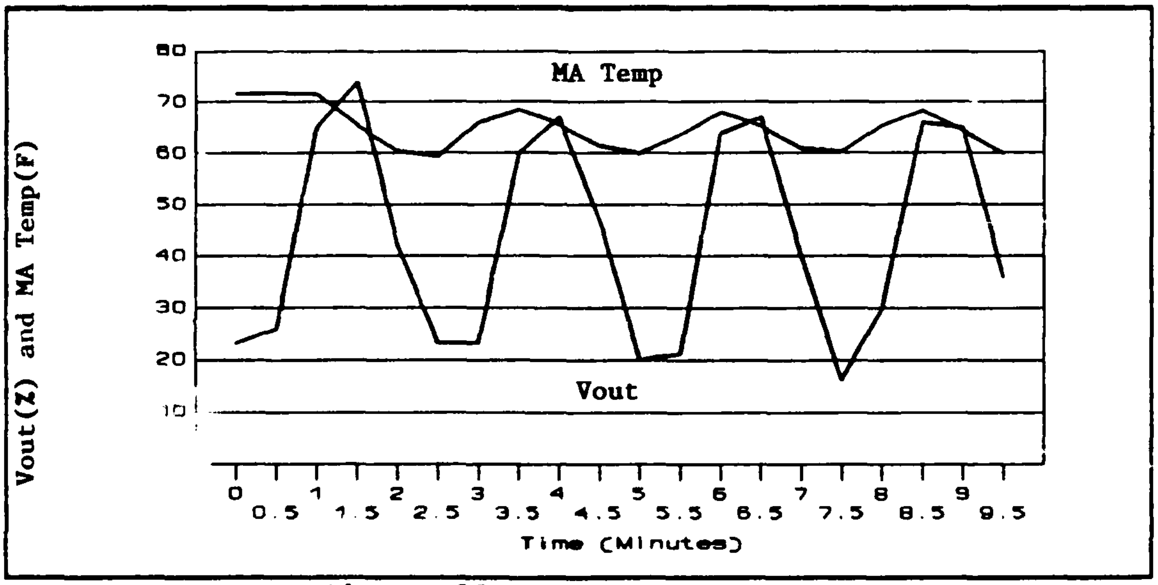


Figure 22. System Response
(Setpoint = 64, PB = 25, Tn = 70)

Table 19. Mixed Air Calibration.
(PB = 25, Setpoint = 68, Tn = 80)

Time (minutes)	Vout (% voltage)	MA Temp (oF)
0.0	38.0	67.2
0.5	25.0	66.1
1.0	29.0	68.2
1.5	40.0	69.8
2.0	45.0	69.1
2.5	34.0	67.0
3.0	27.0	67.2
3.5	34.0	68.9
4.0	42.0	69.4
4.5	40.0	68.2
5.0	32.4	67.0
5.5	30.0	67.7
6.0	35.0	68.6
6.5	38.8	69.0
7.0	39.8	68.6
7.5	37.2	68.0
8.0	34.8	67.8
8.5	33.0	67.9
9.0	32.3	68.1
9.5	32.3	68.1

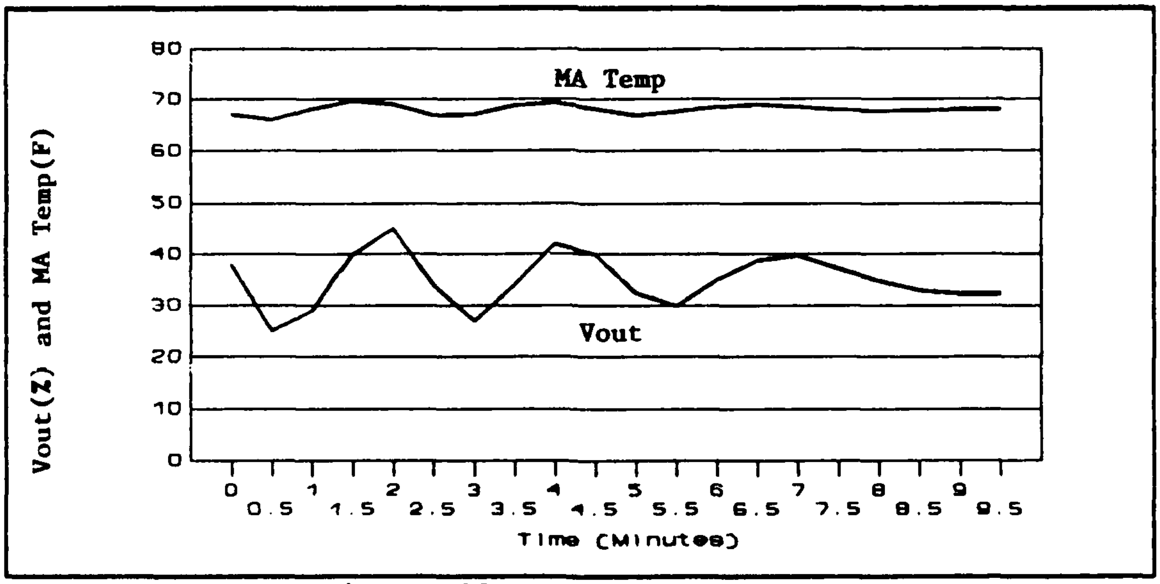


Figure 23. System Response
(Setpoint = 68, PB = 25, Tn = 80)

Table 20. Mixed Air Calibration.
(PB = 25, Setpoint = 64, Tn = 90)

Time (minutes)	Vout (% voltage)	MA Temp (oF)
0.0	57.0	68.3
0.5	41.0	63.1
1.0	30.5	62.3
1.5	42.0	65.8
2.0	48.0	65.8
2.5	42.0	63.7
3.0	38.0	63.5
3.5	36.3	63.6
4.0	39.0	64.5
4.5	41.0	64.8
5.0	42.8	64.9
5.5	43.8	64.8
6.0	44.2	64.7
6.5	45.2	64.7
7.0	44.6	64.5
7.5	43.1	64.3
8.0	42.9	64.3
8.5	41.9	64.2
9.0	41.4	64.2
9.5	40.3	64.2

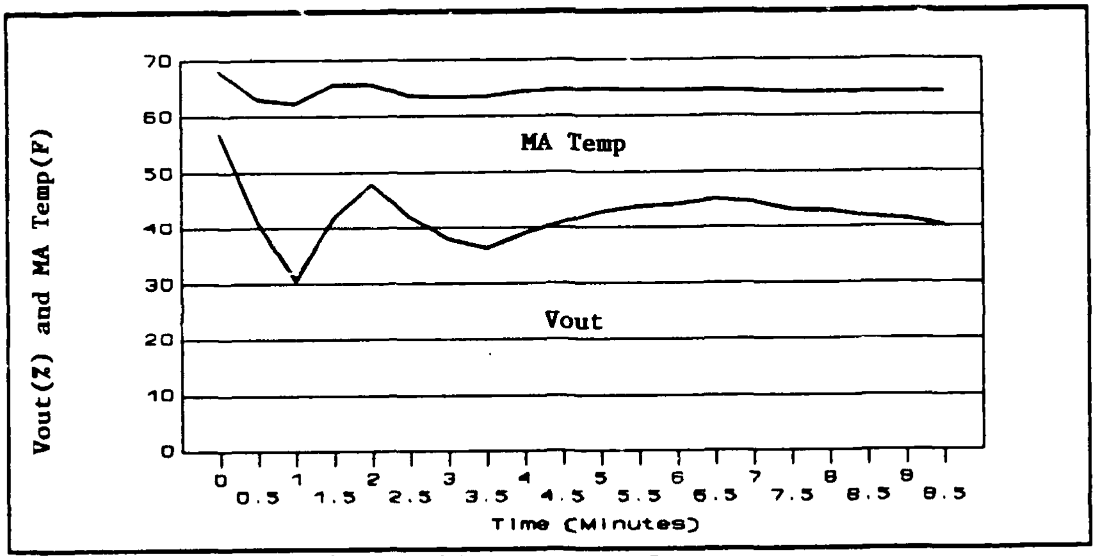


Figure 24. System Response
(Setpoint = 64, PB = 25, Tn = 90)

Table 21. Mixed Air Calibration.
(PB = 25, Setpoint = 68, Tn = 100)

Time (minutes)	Vout (% voltage)	MA Temp (oF)
0.0	19.0	64.5
0.5	29.0	68.0
1.0	39.5	70.5
1.5	42.2	70.3
2.0	34.0	68.4
2.5	30.6	68.2
3.0	31.9	68.8
3.5	33.0	69.1
4.0	33.7	69.2
4.5	34.0	69.2
5.0	34.3	69.3
5.5	34.5	69.3
6.0	35.0	69.3
6.5	35.3	69.4
7.0	35.8	69.4
7.5	36.0	69.4
8.0	36.4	69.4
8.5	36.3	69.3
9.0	36.7	69.3
9.5	36.7	69.3

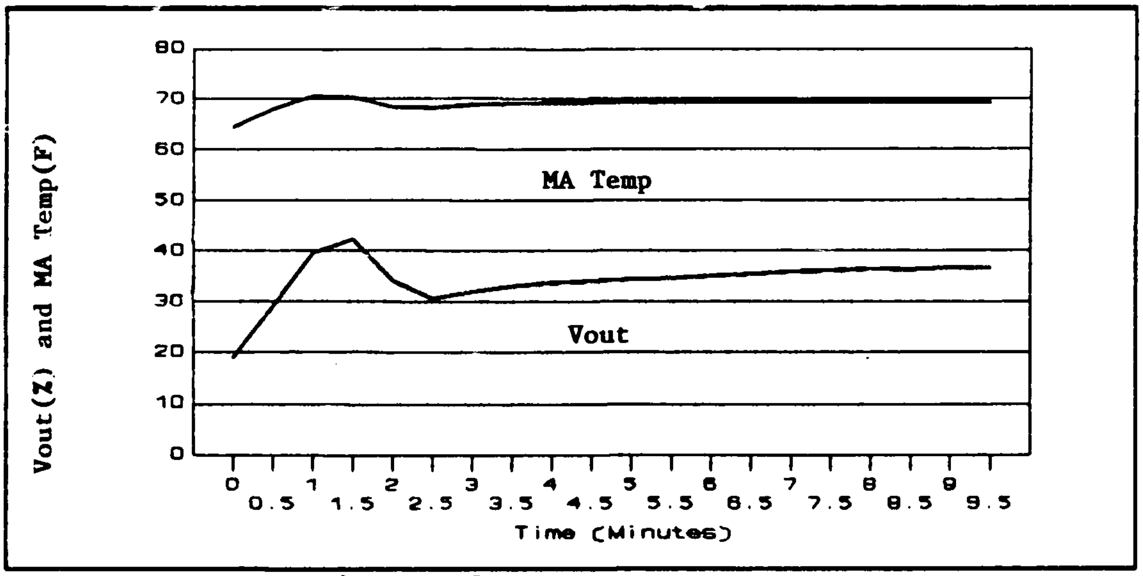


Figure 25. System Response
(Setpoint = 68, PB = 25, Tn = 100)

Table 22. Mixed Air Calibration.
(PB = 30, Setpoint = 64, Tn = 100)

Time (minutes)	Vout (% voltage)	MA Temp (oF)
0.0	57.4	69.2
0.5	47.0	66.0
1.0	34.0	63.4
1.5	35.3	64.8
2.0	39.3	65.9
2.5	41.5	66.2
3.0	42.5	66.3
3.5	43.4	66.3
4.0	43.7	66.2
4.5	43.7	66.0
5.0	43.5	65.9
5.5	43.5	65.8
6.0	43.6	65.8
6.5	43.7	65.8
7.0	43.8	65.8
7.5	43.7	65.8
8.0	43.5	65.7
8.5	43.4	65.7
9.0	43.4	65.7
9.5	43.2	65.7

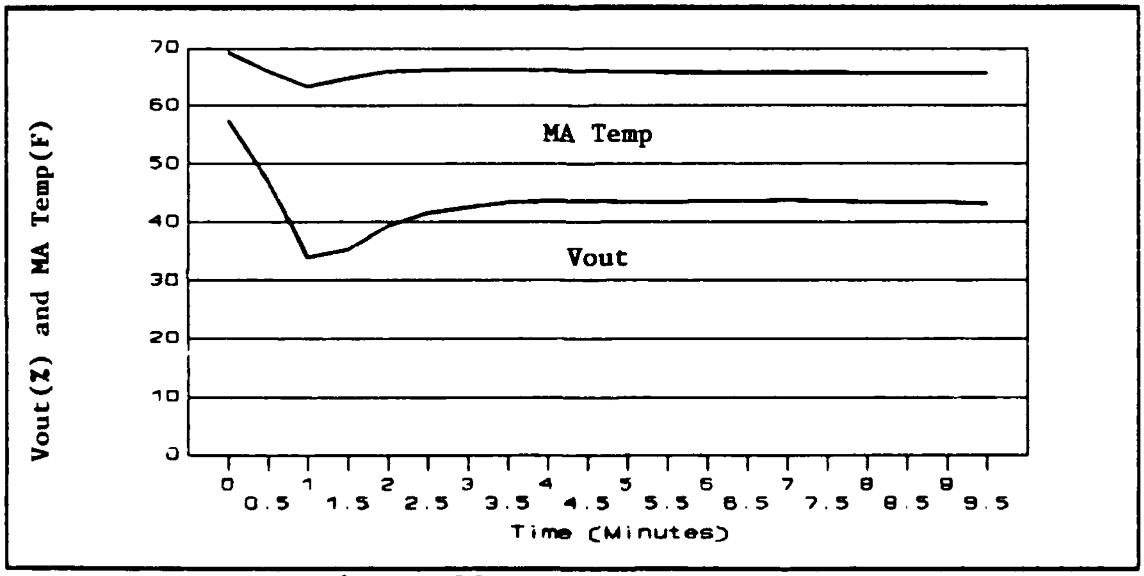


Figure 26. System Response
(Setpoint = 64, PB = 30, Tn = 100)

Table 23. Mixed Air Calibration.
(PB = 30, Setpoint = 68, Tn = 90)

Time (minutes)	Vout (% voltage)	MA Temp (oF)
0.0	28.4	65.7
0.5	32.0	68.3
1.0	39.0	70.1
1.5	42.0	69.8
2.0	38.2	68.5
2.5	34.2	68.0
3.0	32.5	68.0
3.5	32.8	68.3
4.0	32.8	68.6
4.5	32.8	68.6
5.0	32.7	68.6
5.5	32.8	68.6
6.0	32.8	68.6

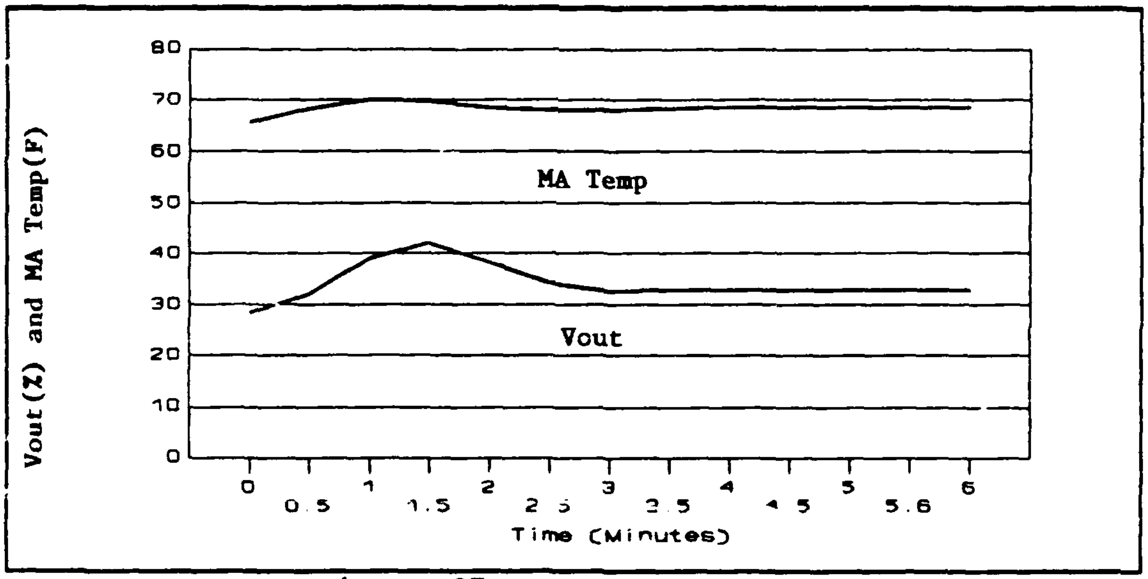


Figure 27. System Response
(Setpoint = 68, PB = 30, Tn = 90)

Table 24. Mixed Air Calibration.
(PB = 30, Setpoint = 64, Tn = 80)

Time (minutes)	Vout (% voltage)	MA Temp (oF)
0.0	55.0	68.6
0.5	55.1	66.2
1.0	42.5	62.5
1.5	31.9	62.0
2.0	38.5	64.8
2.5	49.0	66.1
3.0	50.2	65.1
3.5	42.9	63.6
4.0	37.7	63.1
4.5	39.4	64.1
5.0	42.7	65.0
5.5	46.2	65.1
6.0	47.1	64.8
6.5	46.2	64.4
7.0	45.4	64.2
7.5	44.2	64.2
8.0	43.6	64.1

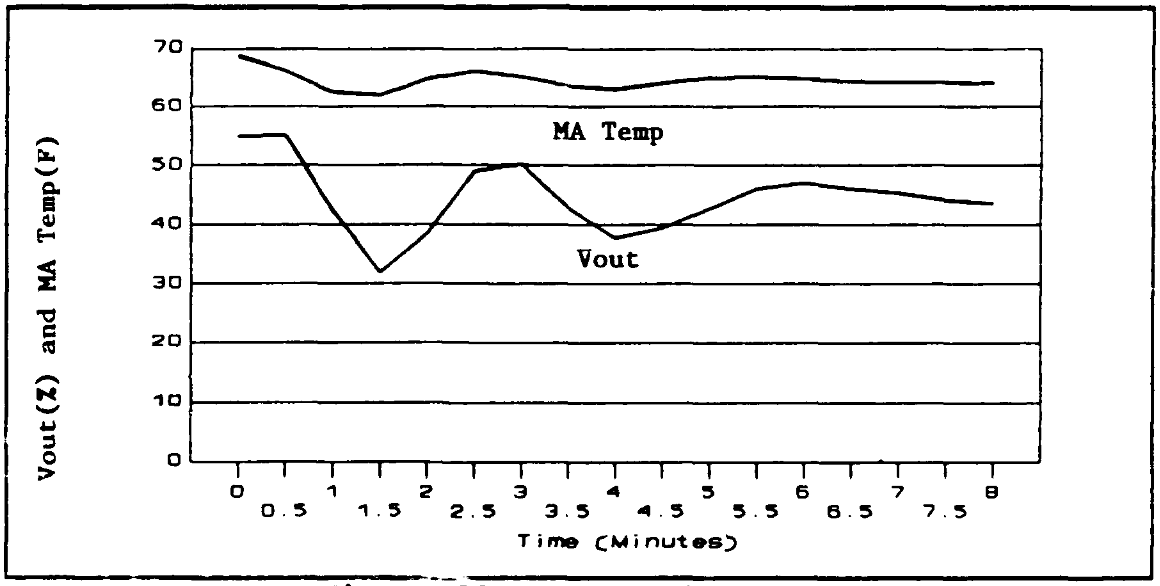


Figure 28. System Response
(Setpoint = 64, PB = 30, Tn = 80)

Table 25. Mixed Air Calibration.
(PB = 30, Setpoint = 68, Tn = 70)

Time (minutes)	Vout (% voltage)	MA Temp (oF)
0.0	5.0	74.1
0.5	40.0	74.0
1.0	65.0	74.0
1.5	70.2	70.7
2.0	56.0	66.4
2.5	30.0	64.5
3.0	22.4	65.9
3.5	32.8	69.0
4.0	50.0	71.1
4.5	57.5	70.0
5.0	48.5	67.1
5.5	35.9	66.1
6.0	32.1	67.3
6.5	41.0	69.2
7.0	49.0	69.8
7.5	51.0	68.8
8.0	43.0	67.0
8.5	35.6	66.8
9.0	36.0	68.0
9.5	41.3	68.9

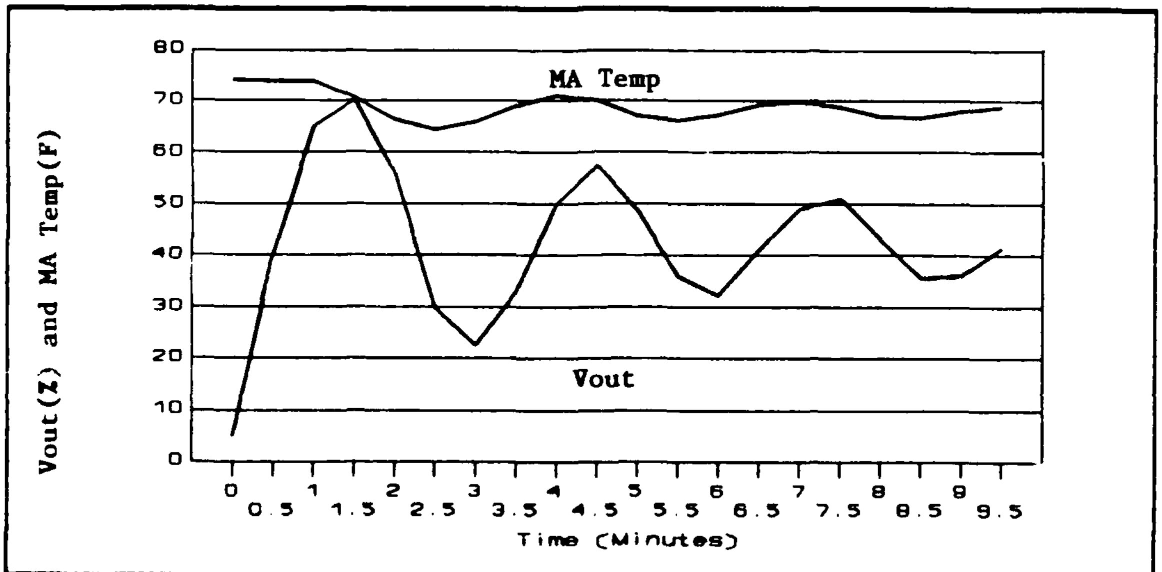


Figure 29. System Response
(Setpoint = 68, PB = 30, Tn = 70)

Table 26. Mixed Air Calibration.
(PB = 20, Setpoint = 68, Tn = 70)

Time (minutes)	Vout (% voltage)	MA Temp (oF)
0.0	56.0	71.2
0.5	67.5	69.4
1.0	53.0	66.7
1.5	32.8	65.7
2.0	27.0	67.2
2.5	48.0	69.8
3.0	63.0	69.9
3.5	51.0	67.4
4.0	33.5	65.9
4.5	31.5	67.5
5.0	47.0	69.9
5.5	62.0	69.5
6.0	45.0	66.5
6.5	32.0	66.5
7.0	32.7	68.3
7.5	50.0	69.7
8.0	60.0	69.1
8.5	47.0	67.1
9.0	35.0	66.5
9.5	34.0	67.7

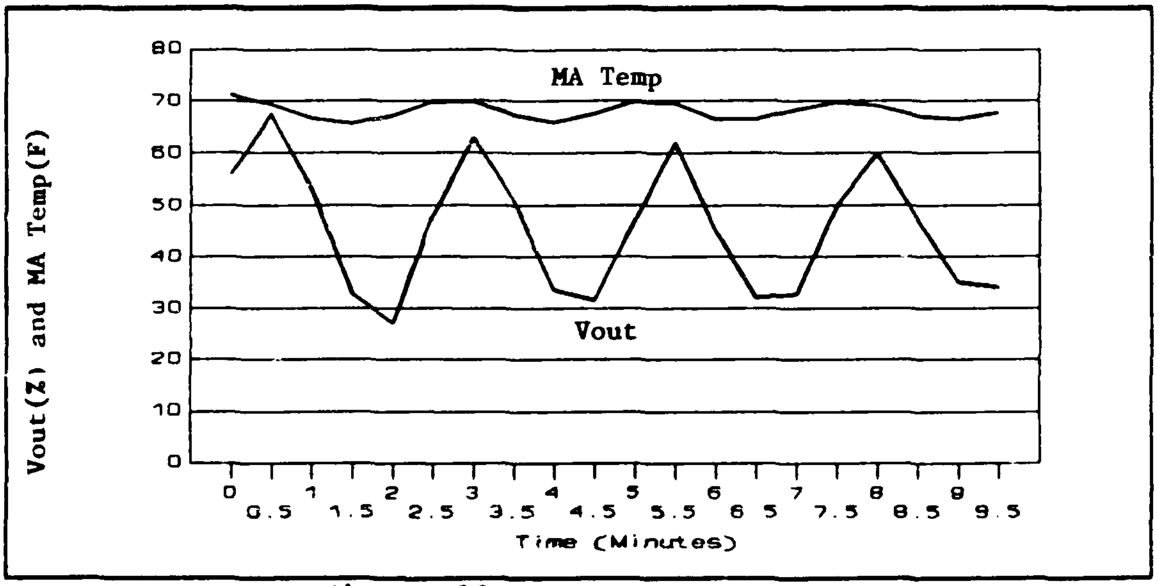


Figure 30. System Response
(Setpoint = 68, PB = 20, Tn = 70)

Table 27. Mixed Air Calibration.
(PB = 20, Setpoint = 68, Tn = 80)

Time (minutes)	Vout (% voltage)	MA Temp (oF)
0.0	50.9	71.7
0.5	68.0	71.4
1.0	55.0	67.5
1.5	35.0	65.9
2.0	32.0	67.5
2.5	43.0	69.0
3.0	55.0	70.0
3.5	51.5	68.3
4.0	41.5	67.0
4.5	36.8	67.3
5.0	41.5	68.5
5.5	49.0	69.0
6.0	52.4	68.9
6.5	49.6	68.1
7.0	46.7	67.7
7.5	42.7	67.5
8.0	41.4	67.7
8.5	42.3	68.0
9.0	44.2	68.4
9.5	44.3	68.2
10.0	47.0	68.5
10.5	46.2	68.1
11.0	48.8	68.5

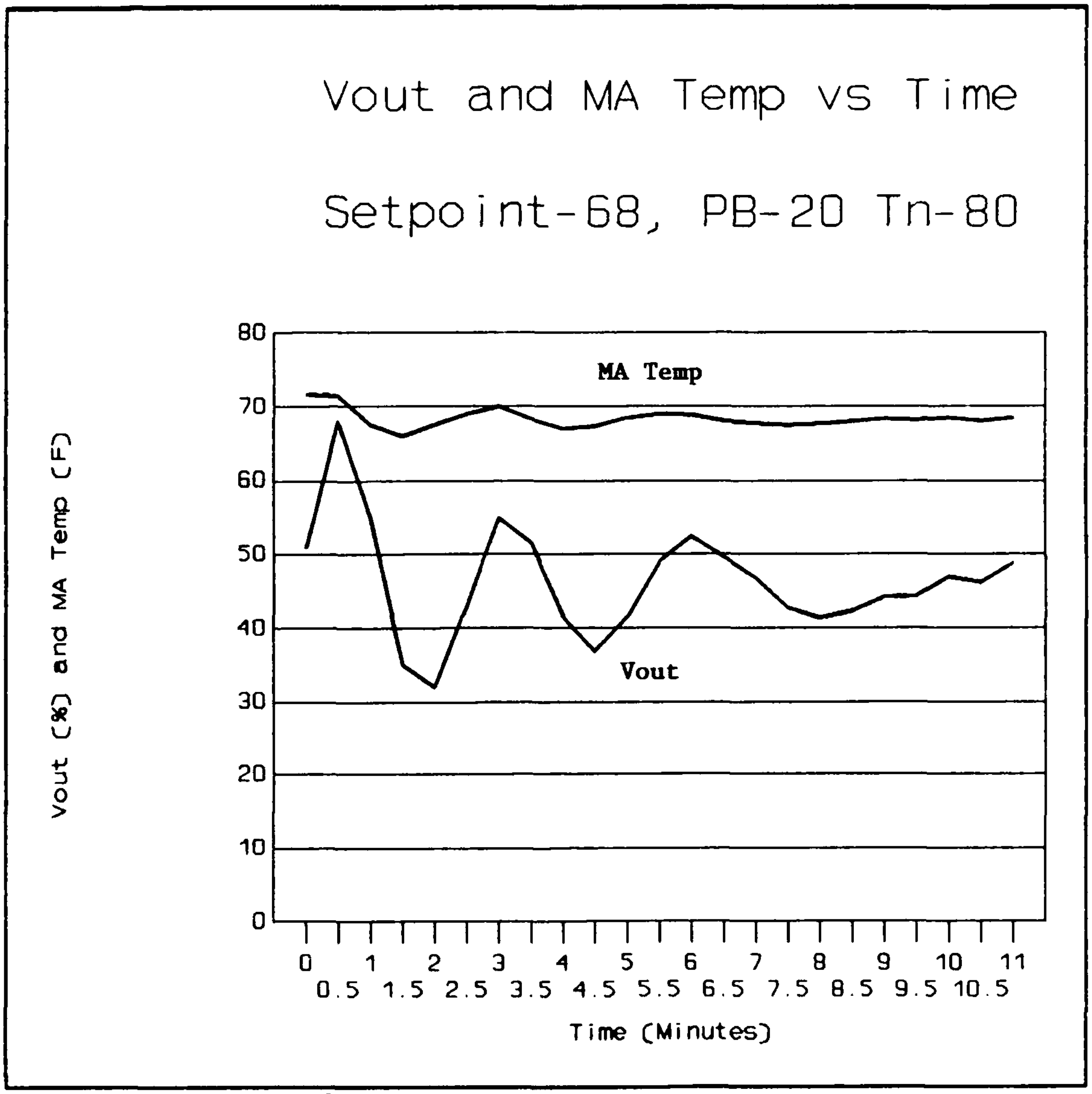


Figure 31. System Response
(Setpoint = 68, PB = 20, Tn = 80)

Table 28. Mixed Air Calibration.
(PB = 20, Setpoint = 69, Tn = 90)

Time (minutes)	Vout (% voltage)	MA Temp (oF)
0.0	42.0	71.5
0.5	59.2	72.1
1.0	53.0	69.9
1.5	44.3	68.8
2.0	38.0	68.2
2.5	37.0	68.7
3.0	43.0	70.0
3.5	48.7	70.4
4.0	51.0	70.3
4.5	49.6	69.7
5.0	44.8	68.9
5.5	42.5	68.9
6.0	40.8	69.0
6.5	42.7	69.5
7.0	44.8	69.8
7.5	43.9	69.5
8.0	43.4	69.4
8.5	42.5	69.4
9.0	44.0	69.6
9.5	43.8	69.5
10.0	44.7	69.6
10.5	46.8	69.8

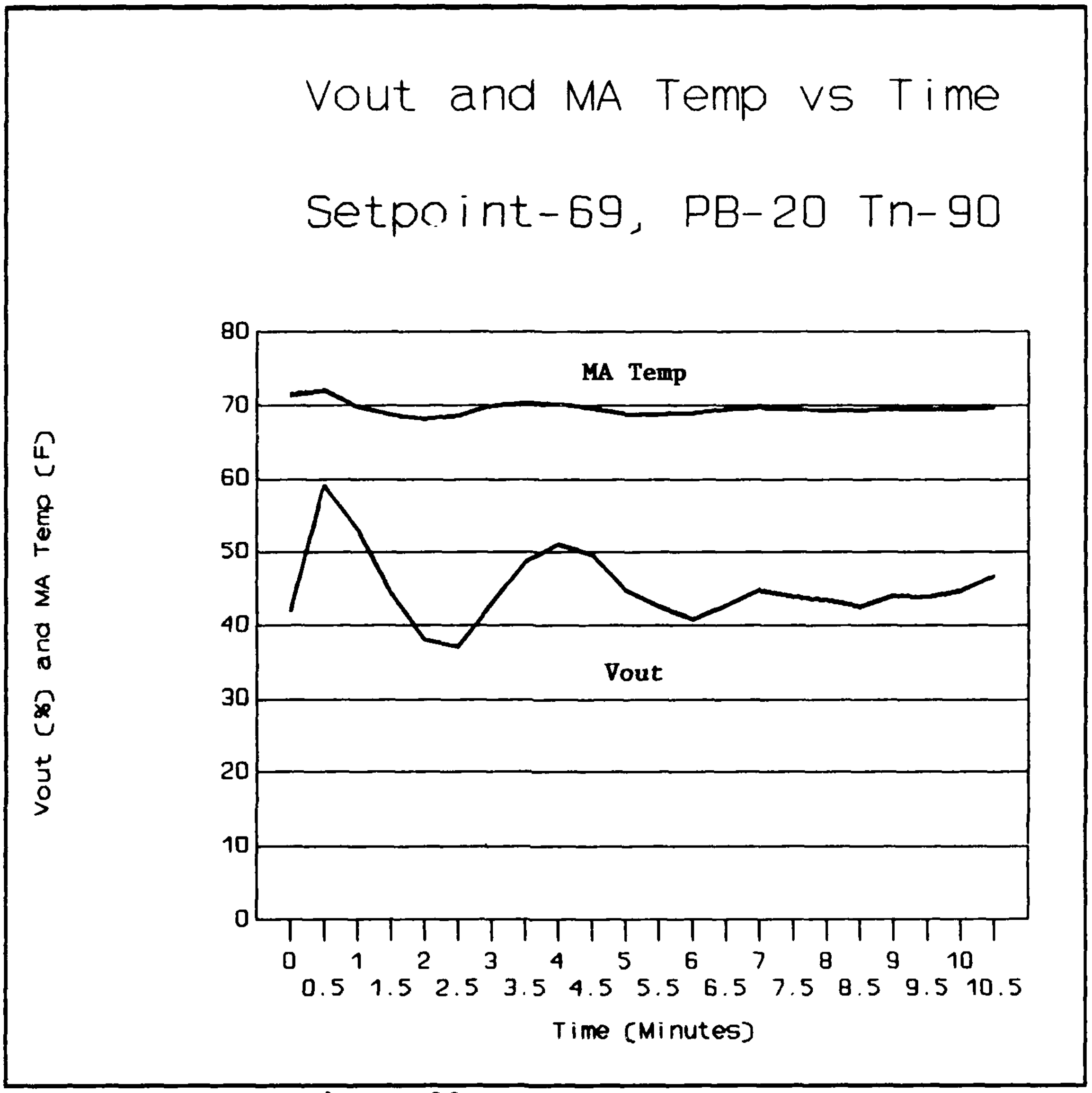


Figure 32. System Response
(Setpoint = 69, PB = 20, Tn = 90)

Table 29. Mixed Air Calibration.
(PB = 20, Setpoint = 69.7, Tn = 100)

Time (minutes)	Vout (% voltage)	MA Temp (oF)
0.0	96.1	66.8
0.5	96.1	66.7
1.0	96.1	66.5
1.5	96.1	66.4
2.0	96.1	66.4
2.5	96.1	66.4
3.0	96.1	66.5
3.5	90.0	66.5
4.0	84.0	66.4
4.5	74.0	66.4
5.0	66.0	66.3
5.5	56.0	66.2
6.0	50.0	66.4
6.5	41.5	66.4
7.0	37.0	66.9
7.5	35.5	67.8
8.0	37.1	69.0
8.5	36.7	69.4
9.0	35.9	69.7
9.5	34.2	69.7
10.0	34.0	70.0
10.5	33.2	70.1
11.0	32.9	70.3
11.5	34.5	70.3

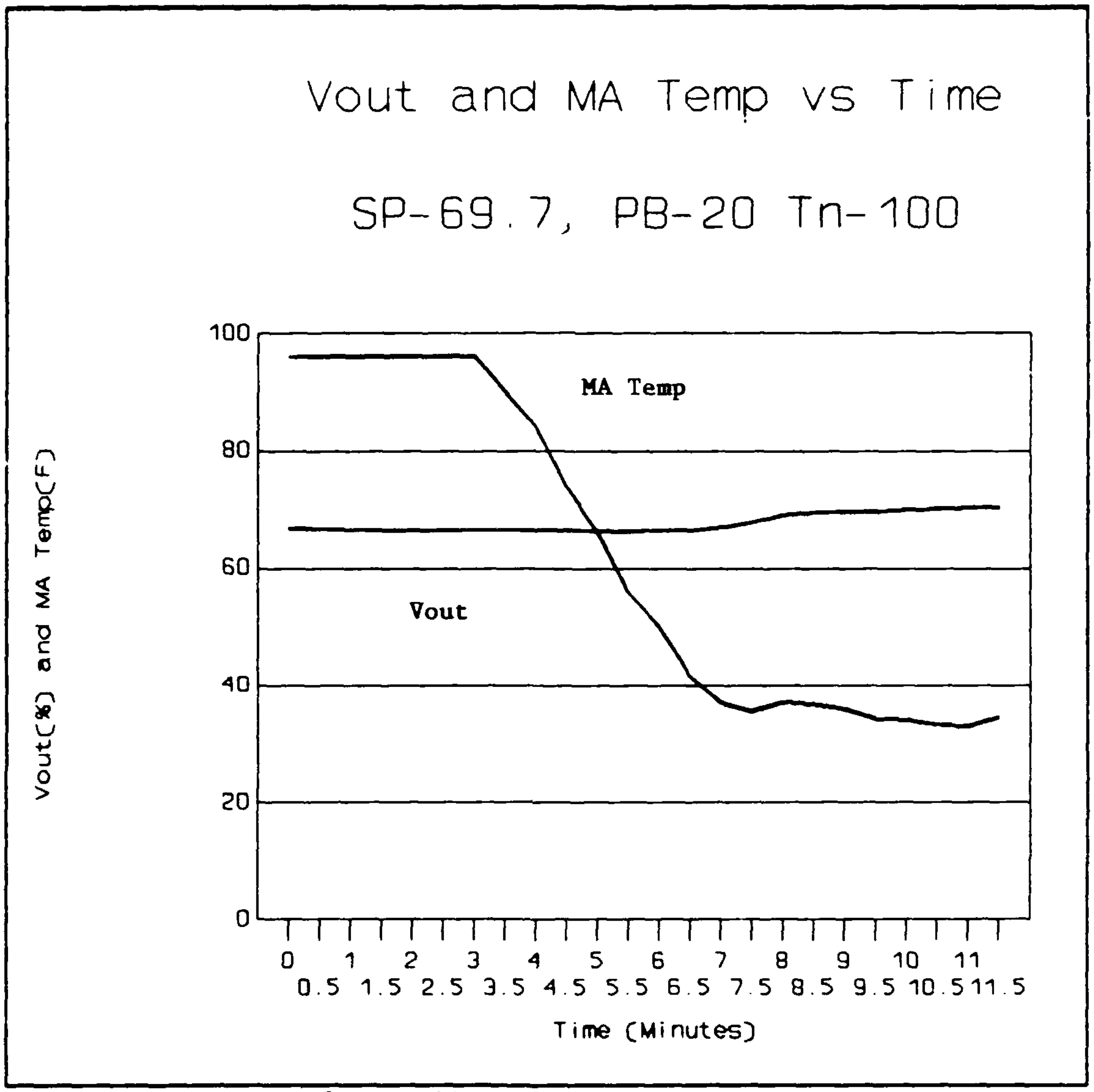


Figure 33. System Response
(Setpoint = 69.7, PB = 20, Tn = 100)

Table 30. Mixed Air Calibration.
(PB = 15, Setpoint = 69.8, Tn = 100)

Time (minutes)	Vout (% voltage)	MA Temp (oF)
0.0	20.1	67.5
0.5	17.0	68.1
1.0	31.4	70.2
1.5	40.0	71.4
2.0	41.8	71.4
2.5	39.1	70.8
3.0	37.1	70.6
3.5	36.4	70.5
4.0	36.1	70.5
4.5	35.7	70.5
5.0	35.4	70.5
5.5	35.3	70.5
6.0	35.0	70.5
6.5	34.8	70.5
7.0	34.5	70.5
7.5	35.0	70.7
8.0	34.7	70.6
8.5	34.2	70.6
9.0	33.9	70.6
9.5	34.0	70.6

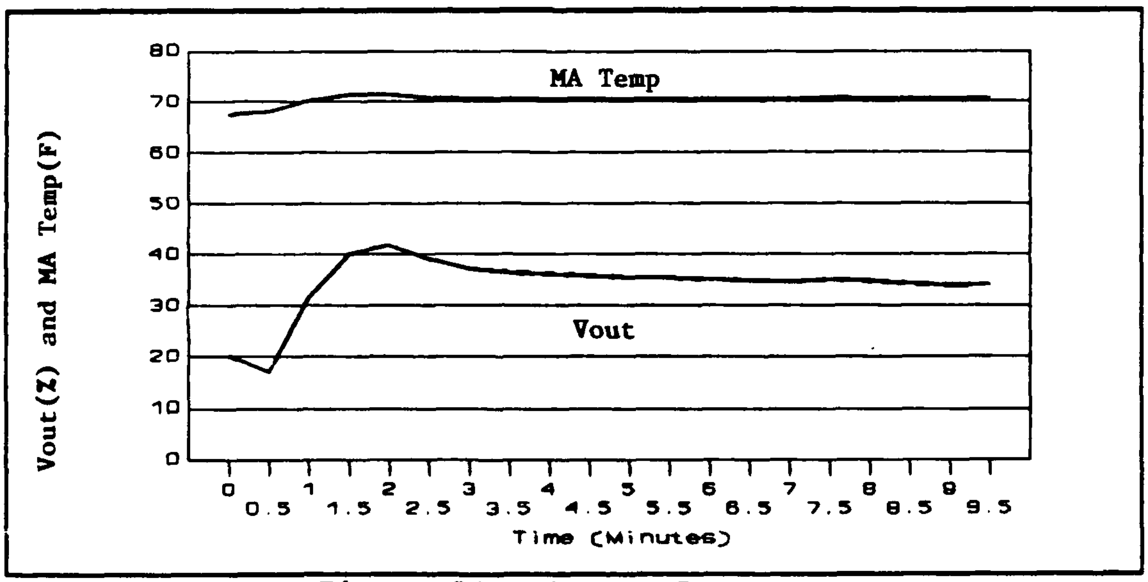


Figure 34. System Response
(Setpoint = 69.8, PB = 15, Tn = 100)

Table 31. Mixed Air Calibration.
(PB = 15, Setpoint = 70, Tn = 90)

Time (minutes)	Vout (% voltage)	MA Temp (oF)
0.0	22.3	68.5
0.5	24.0	69.9
1.0	36.6	71.1
1.5	45.2	71.6
2.0	43.6	71.0
2.5	39.9	70.3
3.0	36.3	70.1
3.5	34.3	70.0
4.0	34.2	70.2
4.5	34.3	70.4
5.0	34.2	70.4
5.5	34.1	70.4
6.0	34.0	70.4
6.5	33.6	70.4
7.0	33.1	70.4
7.5	33.7	70.5
8.0	34.3	70.5
8.5	35.0	70.6
9.0	36.4	70.6
9.5	36.9	70.6

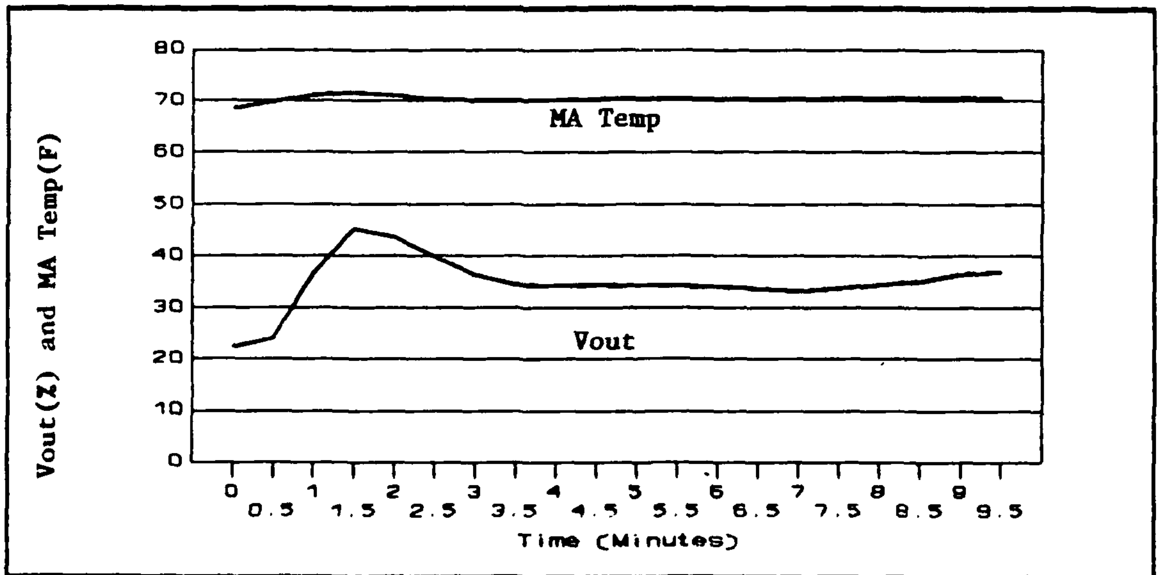


Figure 35. System Response
(Setpoint = 70, PB = 15, Tn = 90)

Table 32. Mixed Air Calibration.
(PB = 15, Setpoint = 71, Tn = 80)

Time (minutes)	Vout (% voltage)	MA Temp (oF)
0.0	40.0	69.9
0.5	21.0	69.9
1.0	33.0	71.7
1.5	44.0	72.0
2.0	45.5	71.4
2.5	37.0	70.7
3.0	32.0	70.4
3.5	31.0	70.7
4.0	34.0	71.2
4.5	36.5	71.3
5.0	39.1	71.3
5.5	39.9	71.2
6.0	39.9	71.1
6.5	39.3	71.0
7.0	38.9	71.0
7.5	38.6	71.0
8.0	38.9	71.0
8.5	38.5	71.0
9.0	37.9	71.0
9.5	37.7	71.0

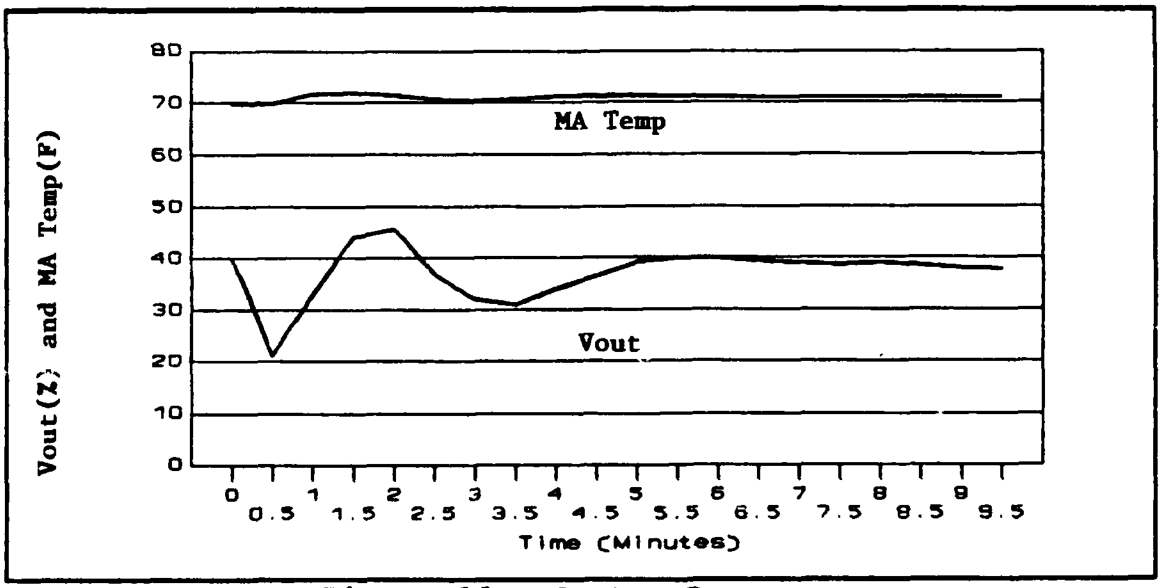


Figure 36. System Response
(Setpoint = 71, PB = 15, Tn = 80)

Table 33. Mixed Air Calibration.
(PB = 15, Setpoint = 71, Tn = 80)

Time (minutes)	Vout (% voltage)	MA Temp (oF)
0.0	46.0	70.0
0.5	18.7	69.2
1.0	27.5	71.1
1.5	39.5	72.1
2.0	48.1	72.1
2.5	44.0	71.0
3.0	36.0	70.4
3.5	31.5	70.5
4.0	32.8	70.9
4.5	35.4	71.2
5.0	37.7	71.2
5.5	39.7	71.3
6.0	40.4	71.2
6.5	40.4	71.2
7.0	40.7	71.1
7.5	40.8	71.1
8.0	40.8	71.0
8.5	41.0	71.0
9.0	41.0	71.0
9.5	40.1	71.0

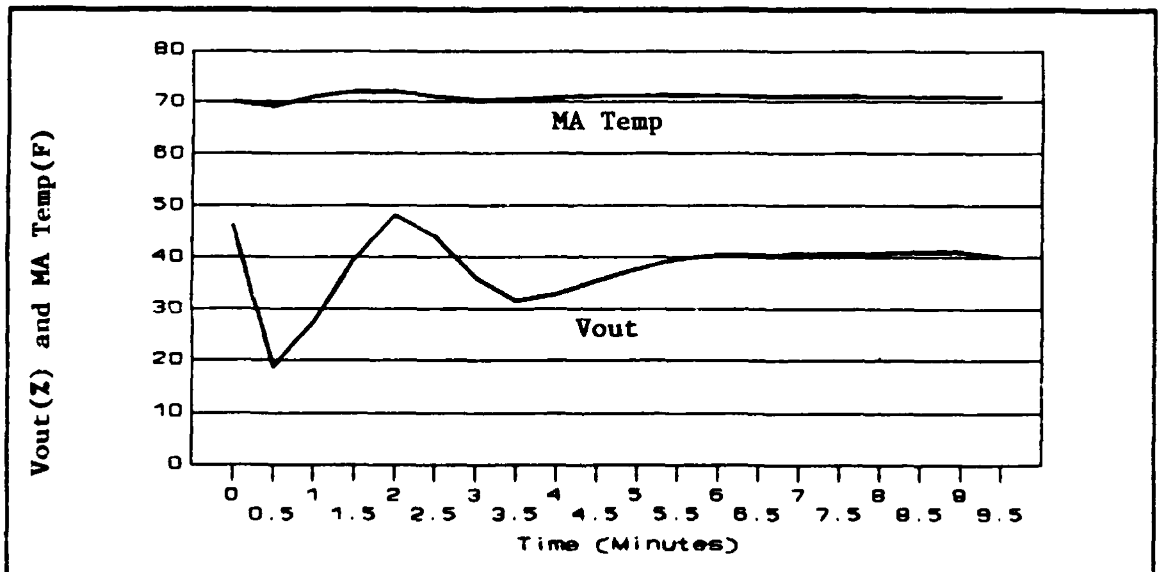


Figure 37. System Response
(Setpoint = 71, PB = 15, Tn = 80)

Table 34. Mixed Air Calibration.
(PB = 15, Setpoint = 71, Tn = 70)

Time (minutes)	Vout (% voltage)	MA Temp (oF)
0.0	63.0	68.1
0.5	33.0	67.5
1.0	1.0	68.0
1.5	5.0	70.9
2.0	27.0	72.3
2.5	54.0	72.9
3.0	63.0	72.3
3.5	40.0	70.0
4.0	24.0	69.0
4.5	20.1	70.2
5.0	35.0	71.9
5.5	51.8	71.1
6.0	51.8	71.1
6.5	37.0	70.0
7.0	27.9	70.2
7.5	34.0	71.1
8.0	42.0	71.6
8.5	47.7	71.5
9.0	44.5	70.7
9.5	35.5	70.3

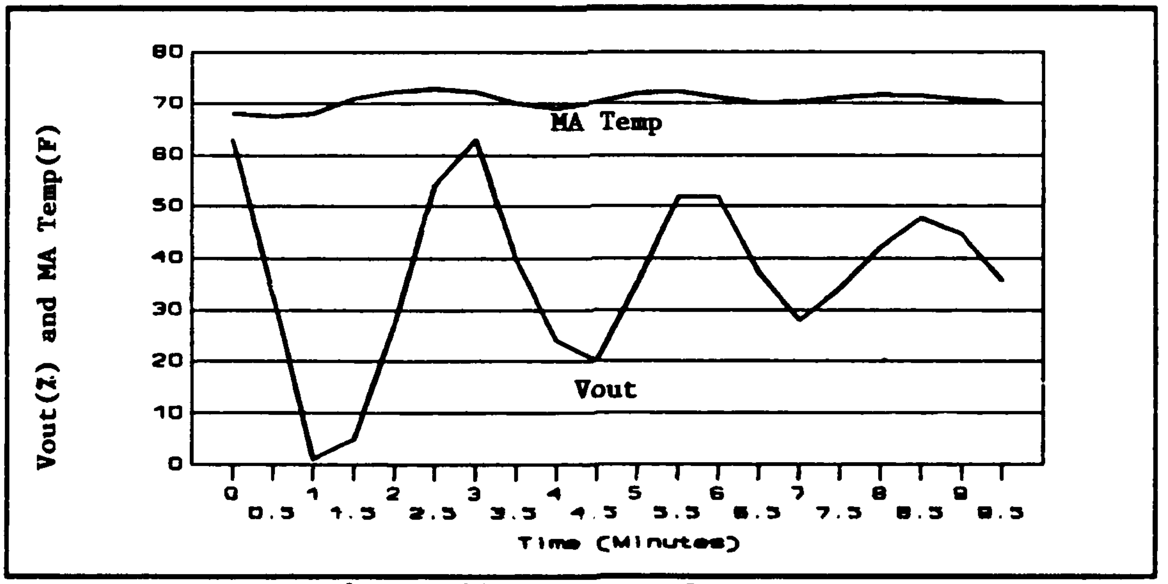


Figure 38. System Response
(Setpoint = 71, PB = 15, Tn = 70)

Appendix C: Civil Engineering Control Shop System Report and Control Scheme
(Reproduced with permission from the 2750th Civil Engineering Control Shop.)

BLDG. 20125 AREA B AHU #7 SERVICING RM 2440

TECHNICIAN: JIM ARNOLD
DATE OF REPORT: SEPT.28, 1988

****

PRELIMINARY FINDINGS:

1. SYSTEM IS VAV WITH DX FOR COOLING AND HOT WATER FOR PREHEAT COIL IN THE AIR HANDLER.
THE VAV BOXES ARE COOLING ONLY WITH ELECTRONIC CONTROLS MOUNTED ON THE BOX. THERE ARE THERMOSTATS IN THE SPACE TO CONTROL THE VAV BOXES.
THE PRIMARY HEAT IS RADIATORS ON THE EXTERIOR WALLS. THE RADIATORS ARE SUPPLIED BY A CONVERTER IN THE EQUIPMENT ROOM, AND TWO VALVES IN THE HOT WATER LINES ABOVE THE CEILING.

2. THIS SYSTEM WAS CONTROLLED BY PNEUMODULAR CONTROLS. THERE HAD BEEN NUMEROUS SERVICE CALLS ON THIS SYSTEM BECAUSE OF WATER AND DIRT IN THE AIR. ALSO, PROBLEMS RELATED WITH PNEUMODULAR CONTROLS (AIR LINES COMING OFF AFTER AGING) CAUSED SERVICE CALLS.

3. THE DUAL INPUT CONTROL FOR THE HOT WATER CONVERTER WAS SETUP TO BE RESET ON OUTSIDE AIR TEMPERATURE, BUT THERE WAS NO SENSOR CONNECTED TO THE RESET PORT OF THIS CONTROLLER. THIS CAUSED MANY OVERHEATING PROBLEMS DURING WINTER OPERATION.

4. THE T&A OPTIMIZER WAS NOT OPERATING PROPERLY AND HAD CAUSED PROBLEMS IN THE PAST.

5. THERE WAS NO DIFFERENTIAL PRESSURE SWITCH IN THE SUPPLY AIR AND THE DX COOLING WAS NOT INTERLOCKED WITH THE AIR HANDLER. IF THE AIR FLOW STOPPED THE DX COULD CONTINUE TO RUN UNTIL FREEZE UP.

6. THE VAV BOXES WERE NOT CALIBRATED AND DID NOT WORK CORRECTLY. SOME WERE OPEN AND SOME CLOSED ALL THE TIME.

7. THE ELECTRIC SUPPLIED TO THE EQUIPMENT ROOM WAS ON ONE BREAKER. THIS INCLUDED THE SOLENOIDS FOR THE DX, THE TRANSFORMER FOR THE VAV BOXES, THE EQUIPMENT ROOM LIGHTING, AND THE AIR COMPRESSOR.

8. FOUND OUTSIDE AIR DAMPERS LOCKED SHUT WITH A SCREW.

****

CORRECTIONS:

1. INSTALLED ALL NEW PNEUMATIC CONTROLS, HONEYWELL RP908 INSTALLED NEW PRESSURE/ELECTRIC SWITCHS, TOTALLY REWORKED THE CONTROL PANEL.

2. INSTALLED DUAL INPUT CONTROLLER TO CONTROL THE CONVERTER, BEING RESET ON THE RETURN AIR TEMPERATURE. USING THIS METHOD TO HAVE FEEDBACK FROM THE SPACE.

3. REMOVED THE T&A OPTIMIZER AND INSTALLED AN ELECTRONIC TIME CLOCK. ALSO, INSTALLED A NIGHT THERMOSTAT IN THE SPACE. (SP.55)

4. INSTALLED A DIFFERENTIAL PRESSURE SWITCH IN THE SUPPLY AIR DUCT AND INTERLOCKED THE MECHANICAL COOLING. THE LIQUID LINE SOLENOIDS WILL DROP OUT WHEN AIR FLOW STOPS.

5. INSPECTED AND CALIBRATED ALL VAV CONTROL BOARDS. SET THE CALIBRATION VOLTAGE FOR MAXIMUM AND MINIMUM AIR FLOW, PER THE CALIBRATION PROCEDURE IN THE MANUFACTURE'S MANUAL.

6. CALLED ELECTRICIANS, THEY REWIRED THE POWER TO THE EQUIPMENT ROOM. THE CONTROL PANEL IS NOW ON A SEPARATE BREAKER.

7. CHECKED CALIBRATION OF ALL SENSORS.

8. CHECKED OPERATION OF ALL DAMPERS AND ACTUATORS.

9. CALIBRATED ALL CONTROLLERS AND LOCKED THE PANEL.

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****

SPECIAL NOTE:

THIS SYSTEM IS BEING USED BY THE AFIT SCHOOL FOR STUDY OF THE CERL CONTROL PANEL.

CAPT. RUMSEY, WITH THE AID OF AFIT, HAS INSTALLED THE CERL PANEL AND RELATED SENSORS PARALLEL WITH THE CONTROL SHOP'S PANEL. THE INSTRUMENT CONTROL SHOP'S PANEL IS THE MAIN CONTROL AT THIS TIME. THE CERL PANEL CAN BE SWITCHED IN FOR SHORT TERM TESTING.

SEQUENCE OF OPERATION:

THIS SYSTEM IS ON A TIME CLOCK. THE AIR HANDLER WILL CYCLE ON AT 05:00 AND CYCLE OFF AT 18:00. THE NIGHT THERMOSTAT WILL CYCLE THE AIR HANDLER ON IF THE SPACE TEMPERATURE DROPS BELOW 55 DEGREES.

WINTER:

WHEN THE AIR HANDLER IS CYCLED ON THE DISCHARGE AIR CONTROLLER WILL MODULATE THE HEATING VALVE TO TEMPER THE AIR AND MAINTAIN 55 DEGREES. IF THE RETURN AIR IS 72 DEGREES OR ABOVE THE WARM-UP RELAY WILL SWITCH ALLOWING THE MIXED AIR CONTROLLER TO MODULATE THE OUTSIDE AND RETURN AIR DAMPERS. THE MIXED AIR SET POINT IS 55 DEGREES. IF THE RETURN AIR IS BELOW 72 DEGREES, THE WARM-UP RELAY WILL DISABLE THE MIXED AIR CONTROLLER. THE OUTSIDE AIR DAMPERS WILL BE CLOSED AND THE RETURN AIR DAMPERS WILL BE OPENED.

THE PRIMARY HEAT IS THE RADIATORS. THE TEMPERATURE OF THE HOT WATER SUPPLING THESE RADIATORS IS CONTROLLED BY THE DUAL INPUT CONTROLLER, HW TEMPERATURE BEING RESET USING THE TEMPERATURE OF THE RETURN AIR. (SEE THE RESET SCHEDULE)

THE VAV BOXES WILL MODULATE IN THE SPACE TO MAINTAIN THE SET POINT OF THE ROOM THERMOSTATS.

SUMMER:

AS THE OUTSIDE TEMPERATURE GOES ABOVE 60 DEGREES THE CHANGEOVER CONTROLLER WILL SWITCH THE RELAYS FOR SUMMER/WINTER CHANGEOVER. THIS WILL LOCK OUT THE MIXED AIR CONTROLLER, CLOSE THE OUTSIDE AIR DAMPERS, AND DIRECT THE DISCHARGE AIR CONTROLLER OUTPUT TO THE PE SWITCHES. THE PE SWITCHES WILL STAGE THE MECHANICAL COOLING ON DEMAND TO MAINTAIN 55 DEGREES DISCHARGE AIR.

THE VAV BOXES WILL MODULATE IN THE SPACE TO MAINTAIN THE SET POINT OF THE ROOM THERMOSTATS.

GENERAL:

THE SYSTEM IS PROTECTED WITH A FREEZE STAT, SMOKE DETECTOR, AND DP SWITCH.

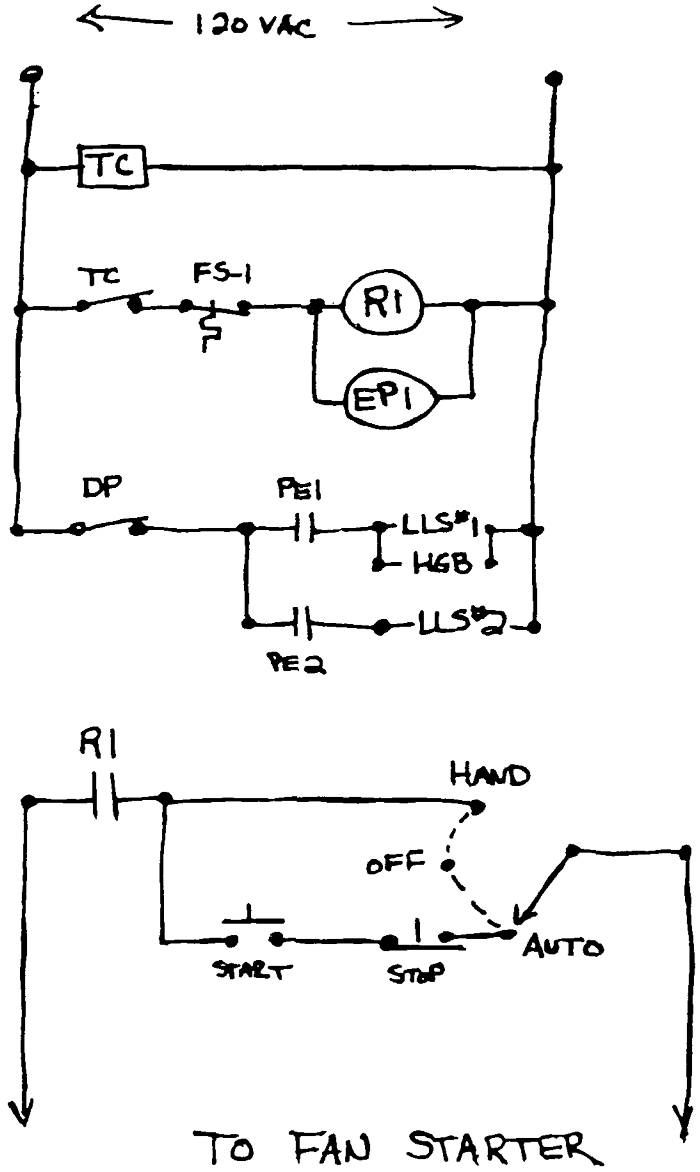
THERE IS A STATIC PRESSURE SENSOR IN THE SUPPLY AIR DUCT THAT IS FED TO THE STATIC PRESSURE CONTROLLER. THIS CONTROLLER IS SET FOR 2", AND WILL MODULATE THE VORTEX VANES IN THE BLOWER TO MAINTAIN PROPER STATIC PRESSURE.

THERE IS A HAND-OFF-AUTO SWITCH IN THE START-STOP STATION. THERE IS A START-STOP STATION FOR TWO HOT WATER PUMPS IN THE SYSTEM.

BILL OF MATERIALS:

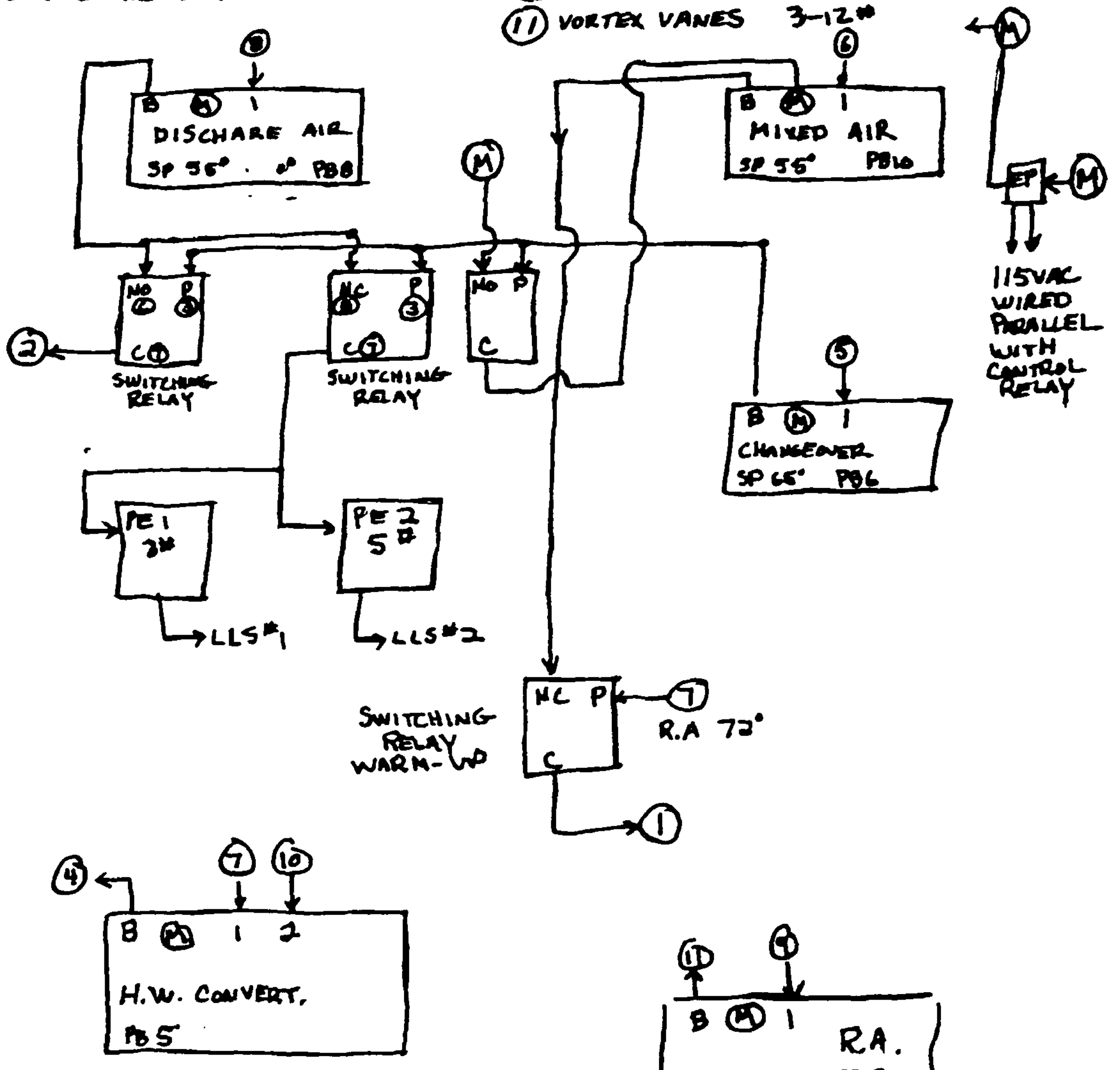
1. O.A. SENSOR --- ROBERTSHAW T150 -25-125 DEGREES
2. R.A. SENSOR --- ROBERTSHAW T150 0-100 DEGREES
3. M.A. SENSOR --- ROBERTSHAW T150 0-100 DEGREES
4. D.A. SENSOR --- ROBERTSHAW T150 40-140 DEGREES
5. D.A. CONTROL -- HONEYWELL RP908 SETPOINT 55
6. M.A. CONTROL -- HONEYWELL RP908 SETPOINT 55
7. S/W CONTROL -- HONEYWELL RP908 SETPOINT 65
8. H.W. CONTROL -- HONEYWELL RP908B
9. STATIC CONTROL -- HONEYWELL RP908 SETPOINT 2"
10. TIMECLOCK --- GRASSLIN
11. S/W RELAY --- HONEYWELL RP471
12. WARM-UP RELAY -- HONEYWELL RP670
13. STATIC PRESS. SENSOR -- ROBERTSHAW 1-3"
14. PE RELAY -- BARBER-COLEMAN

BLDG 125 AREA B ROOM 2413



1 OA/RA DAMPERS 8-11#
2 H.W. ACT. 3-8#
3
4 CONVERT ACT. 3-7#
5 OUTSIDE AIR SENSOR -25-125°

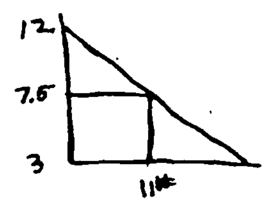
6 MIXED AIR SENSOR 0-100°
7 RETURN AIR SENSOR 0-100°
8 DISCHARGE AIR SENSOR 40-140°
9 STATIC PRESSURE SEN. 3" 3-15#
10 HWS SENSOR 40-240°
11 VORTEX VANES 3-12#



RA.	HW
66	180
72	90

TR1 6° TR2 90°

% AUTH. 13



PB=TR SPAN

VAV BOXES

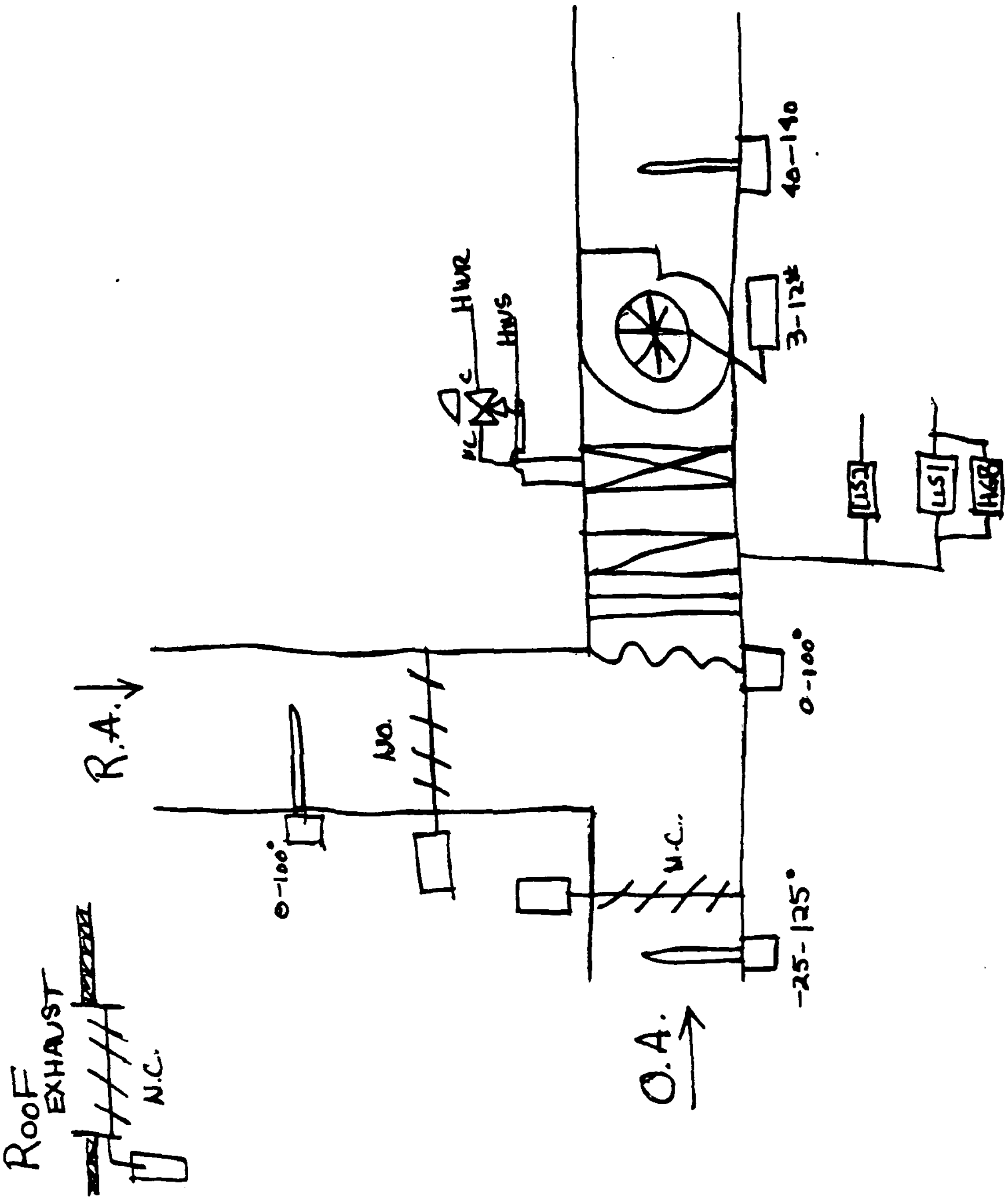
	CFM	FPM	A	MAX VOLTS	MIN VOLTS
B1	550	370	1.5	2.96	3.11
B2	940	470	2.0	2.90	3.10
B3	545	360	1.5	2.98	3.10
B4	340	425	.8	2.94	3.11
B5	760	500	1.5	2.88	3.10
B6	720	480	1.5	2.90	3.10
B7	285	350	.8	2.98	3.12
B8	670	450	1.5	2.92	3.11
B9	670	450	1.5	2.92	3.11
B10	1140	570	2.0	2.84	3.10
B11	445	300	1.5	3.00	3.12
B12	200	250	.8	3.05	3.12
B13	935	620	1.5	2.80	3.08

CFM = AREA x VEL.

$$V = \frac{CFM}{A}$$

MAX = V

MIN = .20 x V


ROOF
EXHAUST
N.C.
R.A.
N.O.
0-100°
N.C.
O.A.
-25-125°
0-100°
HWR
HWS
NC
C
3-12"
40-140
LLS2
LLS1

```
                         SAVE SYSTEM FILE      (STATISTIX)

WEEK      BUMAGUAGE BUMAPANEL MAPANEL   BUSAGUAGE BUSAPANEL SAPANEL   FBUMAGUAG
RBUMAGUAG FBUMAPANE RBUMAPANE RMAPANEL  FMAPANEL  RBUSAGUAG FBUSAGUAG FBUSAPANE
RBUSAPANE FSAPANEL  RSAPANEL

19 variable(s), 29 cases, 29 selected. 101 free var(s), 32089 free items.
-------------------------------------------------------------------------------

Enter the output file name.
> C:\SX\THESIS2
```

```
     WEEK = Week number data was collected
BUMAGUAGE = Built-up system, mixed air controller data, collected by gauge
BUMAPANEL = Built-up system, mixed air controller data, collected by Panel
  MAPANEL = Panel system, mixed air controller data
BUSAGUAGE = Built-up system, supply air controller data, collected by gauge
BUSAPANEL = Built-up system, supply air controller data, collected by Panel
  SAPANEL = Panel system, supply air controller data
FBUMAGUAG = Fitted valves from BUMAGUAGE
RBUMAGUAG = Residuals from BUMAGUAGE
FBUMAPANE = Fitted valves from BUMAPANEL
RBUMAPANE = Residuals from BUMAPANEL
 RMAPANEL = Residuals from MAPANEL
 FMAPANEL = Fitted valves from MAPANEL
RBUSAGUAG = Residuals from BUSAGUAGE
FBUSAGUAG = Fitted valves from BUSAGUAGE
FBUSAPANE = Fitted valves from BUSAPANEL
RBUSAPANE = Residuals from BUSAPANEL
 FSAPANEL = Fitted valves from SAPANEL
 RSAPANEL = Residuals from SAPANEL
```

VIEW DATA (STATISTIX)

CASE	WEEK	BUMAGUAGE	BUMAPANEL	MAPANEL
1	1.0000	1.8000	0.8000	0.0000
2	2.0000	1.1000	0.3000	0.1000
3	3.0000	0.5000	5.5000	0.1000
4	4.0000	2.7000	3.0000	0.1000
5	5.0000	0.3000	0.3000	0.1000
6	6.0000	0.3000	0.3000	0.1000
7	7.0000	0.3000	0.3000	0.1000
8	8.0000	0.0000	0.0000	0.0000
9	9.0000	0.0000	0.0000	0.1000
10	10.000	0.0000	0.0000	0.1000
11	11.000	0.0000	0.0000	0.1000
12	12.000	0.0000	0.0000	0.1000
13	13.000	0.0000	0.0000	0.1000
14	14.000	0.0000	0.0000	0.1000
15	15.000	0.0000	0.0000	0.1000
16	16.000	0.0000	0.0000	0.2000
17	17.000	0.0000	0.0000	0.1000
18	18.000	0.0000	0.0000	0.3000
19	19.000	0.0000	0.0000	0.1000
20	20.000	0.0000	0.0000	0.0000
21	21.000	2.3000	4.0000	1.1000
22	22.000	0.0000	0.0000	0.3000
23	23.000	0.0000	0.0000	0.0000
24	24.000	0.0000	0.0000	0.0000
25	25.000	1.7000	0.0000	0.0000
26	26.000	5.0000	5.0000	0.0000
27	27.000	0.0000	0.0000	0.0000
28	28.000	0.0000	0.0000	0.0000
29	29.000	0.0000	0.0000	0.0000

VIEW DATA (STATISTIX)

CASE	WEEK	BUSAGUAGE	BUSAPANEL	SAPANEL
1	1.0000	0.0000	0.0000	3.0000
2	2.0000	0.5000	0.5000	4.5000
3	3.0000	0.0000	0.0000	5.0000
4	4.0000	0.0000	0.0000	0.0000
5	5.0000	0.0000	0.0000	0.0000
6	6.0000	0.0000	0.0000	0.0000
7	7.0000	0.0000	0.0000	0.0000
8	8.0000	0.0000	0.0000	0.0000
9	9.0000	0.0000	0.0000	0.0000
10	10.000	0.0000	0.0000	0.0000
11	11.000	0.0000	0.0000	2.5000
12	12.000	0.0000	0.0000	3.7000
13	13.000	0.0000	0.0000	2.8000
14	14.000	0.0000	0.0000	3.0000
15	15.000	0.0000	0.0000	5.4000
16	16.000	0.0000	0.0000	3.6000
17	17.000	0.0000	0.0000	4.5000
18	18.000	0.0000	0.0000	0.0000
19	19.000	0.0000	0.0000	5.4000
20	20.000	0.0000	0.0000	0.0000
21	21.000	0.0000	0.0000	5.2000
22	22.000	0.0000	0.0000	4.7000
23	23.000	0.0000	0.0000	0.0000
24	24.000	0.0000	0.0000	0.0000
25	25.000	0.0000	0.0000	5.2000
26	26.000	0.0000	0.0000	5.0000
27	27.000	0.0000	0.0000	4.5000
28	28.000	0.0000	0.0000	5.0000
29	29.000	1.2000	3.4000	4.5000

BUILT-UP SYSTEM (QUATTRO)
MIXED AIR REGRESSION ANALYSIS

WEEKS	BUILT-UP MIXED AIR DRIFT IN PSI (GAUGE)	(PANEL)	REGRESSION VALUES (GAUGE)	(PANEL)
1	1.8	0.8	1.847895	0.970345
2	1.1	0.3	1.709825	0.949064
3	0.5	5.5	1.571754	0.927783
4	2.7	3	1.433684	0.906502
5	0.3	0.3	1.295614	0.885222
6	0.3	0.3	1.157544	0.863941
7	C.3	0.3	1.019474	0.84266
8	0	0	0.881404	0.821379
9	0	0	0.743333	0.800099
10	0	0	0.605263	0.778818
11	0	0	0.467193	0.757537
12	0	0	0.329123	0.736256
13	0	0	0.191053	0.714975
14	0	0	0.052982	0.693695
15	0	0	-0.08509	0.672414
16	0	0	-0.22316	0.651133
17	0	0	-0.36123	0.629852
18	0	0	-0.4993	0.608571
19	0	0	-0.63737	0.587291
20	0	0	-0.77544	0.56601
21	2.3	4	-0.91351	0.544729
22	0	0	-1.05158	0.523448
23	0	0	-1.18965	0.502167
24	0	0	-1.32772	0.480887
25	1.7	0	-1.46579	0.459606
26	5	5	-1.60386	0.438325
27	0	0	-1.74193	0.417044
28	0	0	-1.88	0.395764
29	0	0	-2.01807	0.374483

(QUATTRO)

BUMAGUAGE

Regression Output:

Constant	0.533251
Std Err of Y Est	1.164432
R Squared	8.41E-05
No. of Observations	29
Degrees of Freedom	27

X Coefficient(s)	0.001232
Std Err of Coef.	0.025844

BUMAPANEL

Regression Output:

Constant	0.991626
Std Err of Y Est	1.57784
R Squared	0.013492
No. of Observations	29
Degrees of Freedom	27

X Coefficient(s)	-0.02
Std Err of Coef.	0.035

MULTIPLE REGRESSION (STATISTIX)

```
WEEK      BUMAGUAGE BUMAPANEL MAPANEL   BUSAGUAGE BUSAPANEL SAPANEL

7 variable(s), 29 cases, 29 selected. 113 free var(s), 32437 free items.
```

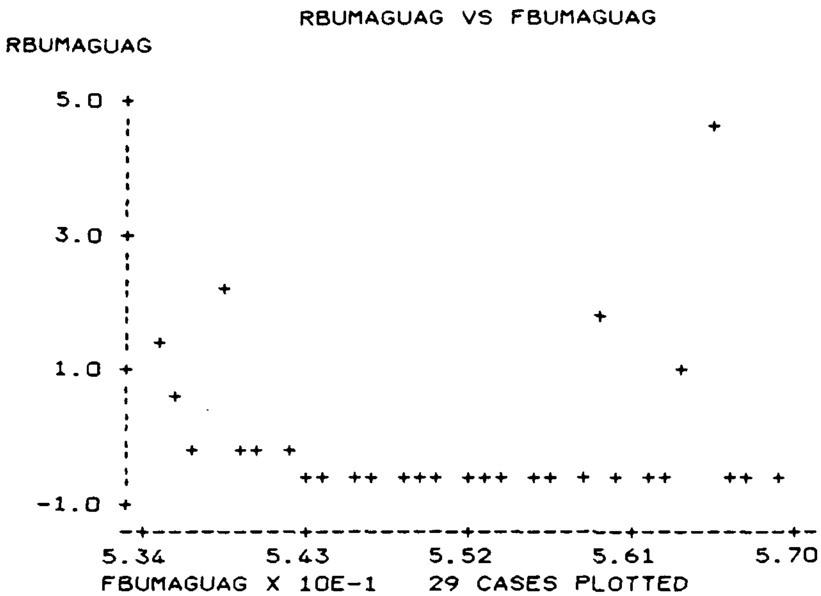
```
Enter regression model: Y = X1 X2 ... (WT = Var, NOCON).
You may enter ALL or use A .. Z syntax.
> BUMAGUAGE=WEEK
```

UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF BUMAGUAGE

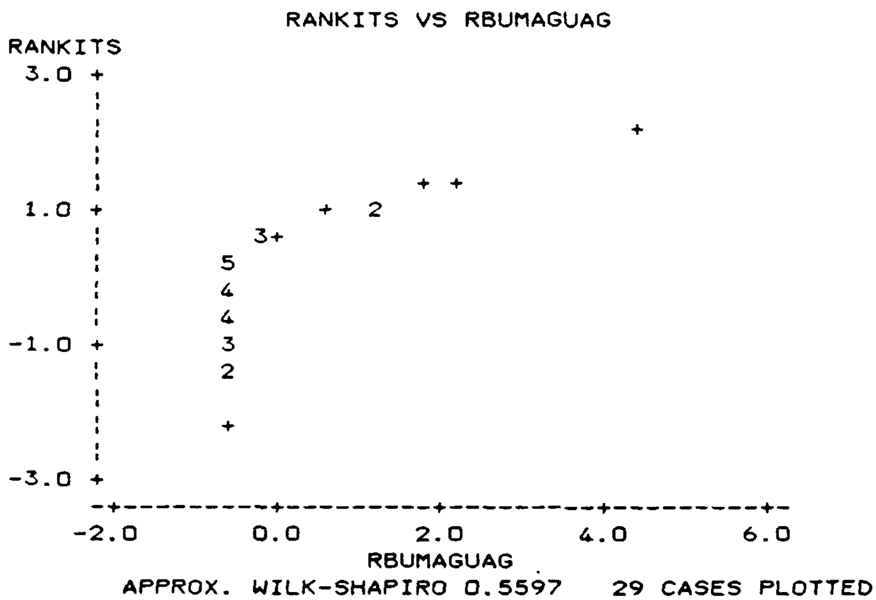
PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	STUDENT'S T	P
CONSTANT	5.3325E-01	4.4389E-01	1.20	0.2401
WEEK	1.2315E-03	2.5844E-02	0.05	0.9623

CASES INCLUDED	29	MISSING CASES	0
DEGREES OF FREEDOM	27		
OVERALL F	2.271E-03	P VALUE	0.9623
ADJUSTED R SQUARED	-0.0369		
R SQUARED	0.0001		
RESID. MEAN SQUARE	1.356		

(STATISTIX)



Assumption of equal variance is not apt.



Assumption of normally distributed error terms is not apt.

MULTIPLE REGRESSION (STATISTIX)

```
WEEK       BUMAGUAGE BUMAPANEL MAPANEL   BUSAGUAGE BUSAPANEL SAPANEL   FBUMAGUAG
RBUMAGUAG

9 variable(s), 29 cases, 29 selected. 111 free var(s), 32379 free items.
```

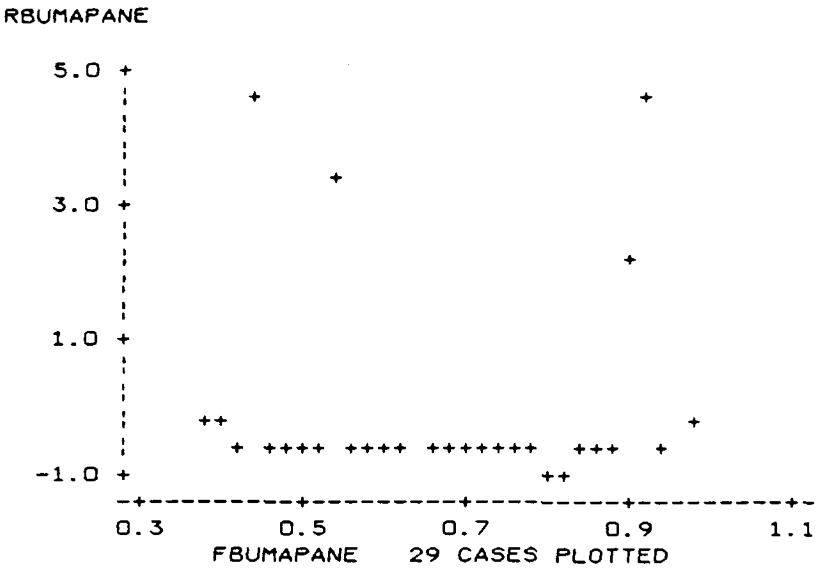
```
Enter regression model: Y = X1 X2 ... (WT = Var, NOCON).
You may enter ALL or use A .. Z syntax.
> BUMAPANEL=WEEK
```

UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF BUMAPANEL

PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	STUDENT'S T	P
CONSTANT	0.9916	6.0149E-01	1.65	0.1108
WEEK	-2.1281E-02	3.5020E-02	-0.61	0.5485

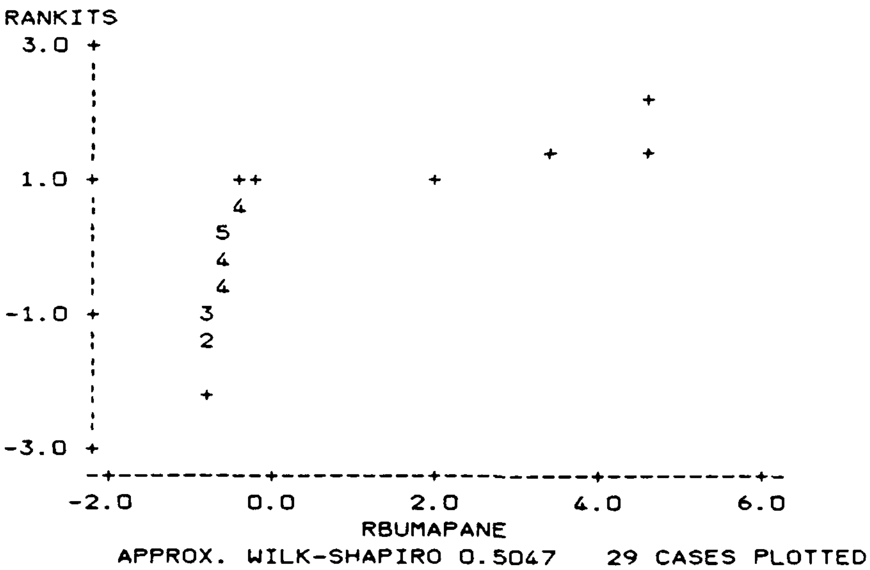
CASES INCLUDED	29	MISSING CASES	0
DEGREES OF FREEDOM	27		
OVERALL F	3.693E-01	P VALUE	0.5485
ADJUSTED R SQUARED	-0.0230		
R SQUARED	0.0135		
RESID. MEAN SQUARE	2.490		

RBUMAPANE VS FBUMAPANE (STATISTIX)



Assumption of equal variance was not apt.

RANKITS VS RBUMAPANE



Assumption of normally distributed error terms was not apt.

BUILT-UP SYSTEM
SUPPLY AIR REGRESSION ANALYSIS

BUILT-UP SUPPLY AIR DRIFT IN PSI		REGRESSION VALUES	
(GAUGE)	(PANEL)	(GAUGE)	(PANEL)
0	0	-0.01241	-0.14897
0.5	0.5	-0.00734	-0.12872
0	0	-0.00227	-0.10847
0	0	0.002808	-0.08823
0	0	0.007882	-0.06798
0	0	0.012956	-0.04773
0	0	0.01803	-0.02749
0	0	0.023103	-0.00724
0	0	0.028177	0.013005
0	0	0.033251	0.033251
0	0	0.038325	0.053498
0	0	0.043399	0.073744
0	0	0.048473	0.09399
0	0	0.053547	0.114236
0	0	0.058621	0.134483
0	0	0.063695	0.154729
0	0	0.068768	0.174975
0	0	0.073842	0.195222
0	0	0.078916	0.215468
0	0	0.08399	0.235714
0	0	0.089064	0.255961
0	0	0.094138	0.276207
0	0	0.099212	0.296453
0	0	0.104286	0.3167
0	0	0.10936	0.336946
0	0	0.114433	0.357192
0	0	0.119507	0.377438
0	0	0.124581	0.397685
1.2	3.4	0.129655	0.417931

BUSAGAUGE (QUATTRO)

Regression Output:

Constant		-0.01749
Std Err of Y Est		0.238676
R Squared		0.032861
No. of Observations		29
Degrees of Freedom		27
X Coefficient(s)	0.005	
Std Err of Coef.	0.005	

BUSAPANEL

Regression Output:

Constant		-0.169212
Std Err of Y Est		0.622224
R Squared		0.0737337
No. of Observations		29
Degrees of Freedom		27
X Coefficient(s)	0.020246305419	
Std Err of Coef.	0.013810161605	

MULTIPLE REGRESSION (STATISTIX)

```
WEEK      BUMAGUAGE BUMAPANEL MAPANEL   BUSAGUAGE BUSAPANEL SAPANEL   FBUMAGUAG
RBUMAGUAG FBUMAPANE RBUMAPANE RMAPANEL  FMAPANEL  RBUSAGUAG FBUSAGUAG

15 variable(s), 29 cases, 29 selected. 105 free var(s), 32205 free items.
```

```
Enter regression model: Y = X1 X2 ... (WT = Var, NOCON).
You may enter ALL or use A .. Z syntax.
> BUSAGUAGE=WEEK
```

UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF BUSAGUAGE

PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	STUDENT'S T	P
CONSTANT	-1.7488E-02	9.0985E-02	-0.19	0.8490
WEEK	5.0739E-03	5.2974E-03	0.96	0.3467

CASES INCLUDED	29	MISSING CASES	0
DEGREES OF FREEDOM	27		
OVERALL F	9.174E-01	P VALUE	0.3467
ADJUSTED R SQUARED	-0.0030		
R SQUARED	0.0329		
RESID. MEAN SQUARE	5.697E-02		

```
                    RBUSAGUAG VS FBUSAGUAG                 (STATISTIX)
RBUSAGUAG

  1.2 +
      :                                      +
      :
      :
      :
  0.7 +
      :
      :   +
      :
      :
  0.2 +
      :
      :  + + +++ ++++ +++
      :                  + ++++ +++ ++++ +++
      :
 -0.3 +
      -+---------+---------+---------+---------+-
    -0.2       0.2       0.6       1.0       1.4
    FBUSAGUAG X 10E-1   29 CASES PLOTTED
```

Assumption of
equal variance
was not apt.

```
                     RANKITS VS RBUSAGUAG
  RANKITS
  3.0 +
      :
      :                                 +
      :
      :      +           +
  1.0 +     2+
      :     4
      :    32
      :    4
      :   3+
 -1.0 +   3
      :   2
      :
      :  +
      :
 -3.0 +
      -+---------+---------+---------+---------+-
    -0.3       0.1       0.5       0.9       1.3
                         RBUSAGUAG
       APPROX. WILK-SHAPIRO 0.4106    29 CASES PLOTTED
```

Assumption of
normally distributed
error terms was not
apt.

MULTIPLE REGRESSION (STATISTIX)

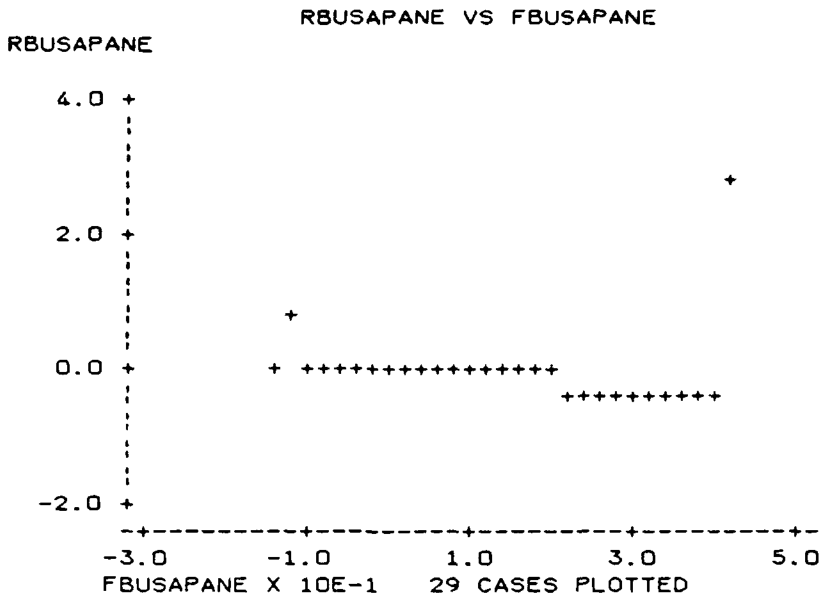
```
WEEK      BUMAGUAGE BUMAPANEL MAPANEL   BUSAGUAGE BUSAPANEL SAPANEL   FBUMAGUAG
RBUMAGUAG FBUMAPANE RBUMAPANE RMAPANEL  FMAPANEL  RBUSAGUAG FBUSAGUAG

15 variable(s), 29 cases, 29 selected. 105 free var(s), 32205 free items.
```

```
Enter regression model: Y = X1 X2 ... (WT = Var, NOCON).
You may enter ALL or use A .. Z syntax.
> BUSAPANEL=WEEK
```

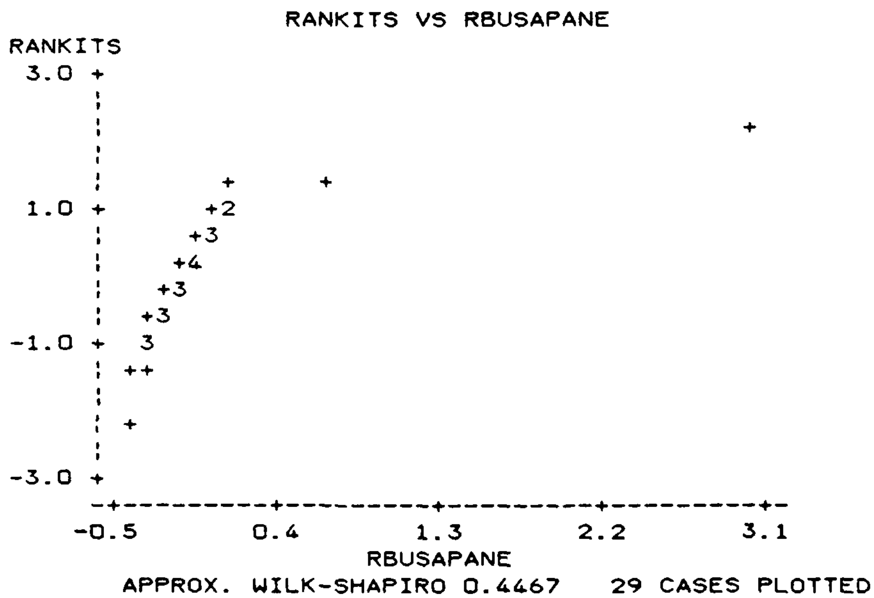
UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF BUSAPANEL

PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	STUDENT'S T	P
CONSTANT	-1.6921E-01	2.3720E-01	-0.71	0.4817
WEEK	2.0246E-02	1.3810E-02	1.47	0.1542

CASES INCLUDED	29	MISSING CASES	0
DEGREES OF FREEDOM	27		
OVERALL F	2.149	P VALUE	0.1542
ADJUSTED R SQUARED	0.0394		
R SQUARED	0.0737		
RESID. MEAN SQUARE	3.872E-01		



Assumption of
equal variance
was not apt.



Assumption of
normally distributed
error terms was not
apt.

PANEL (QUATTRO)

MIXED AIR REGRESSION ANALYSIS

PANEL MIXED AIR DRIFT IN TEMP	REGRESSION VALUES
0	0.103448
0.1	0.104433
0.1	0.105419
0.1	0.106404
0.1	0.107389
0.1	0.108374
0.1	0.10936
0	0.110345
0.1	0.11133
0.1	0.112315
0.1	0.1133
0.1	0.114286
0.1	0.115271
0.1	0.116256
0.1	0.117241
0.2	0.118227
0.1	0.119212
0.3	0.120197
0.1	0.121182
0	0.122167
1.1	0.123153
0.3	0.124138
0	0.125123
0	0.126108
0	0.127094
0	0.128079
0	0.129064
0	0.130049
0	0.131034

PANEL MIXED AIR

Regression Output:

Constant	0.102463
Std Err of Y Est	0.209002
R Squared	0.001668
No. of Observations	29
Degrees of Freedom	27
X Coefficient(s)	0.000985
Std Err of Coef.	0.004639

MULTIPLE REGRESSION (STATISTIX)

```
WEEK        BUMAGUAGE BUMAPANEL MAPANEL   BUSAGUAGE BUSAPANEL SAPANEL   FBUMAGUAG
RBUMAGUAG FBUMAPANE RBUMAPANE

11 variable(s), 29 cases, 29 selected. 109 free var(s), 32321 free items.
```

```
Enter regression model: Y = X1 X2 ... (WT = Var, NOCON).
You may enter ALL or use A .. Z syntax.
> MAPANEL=WEEK
```

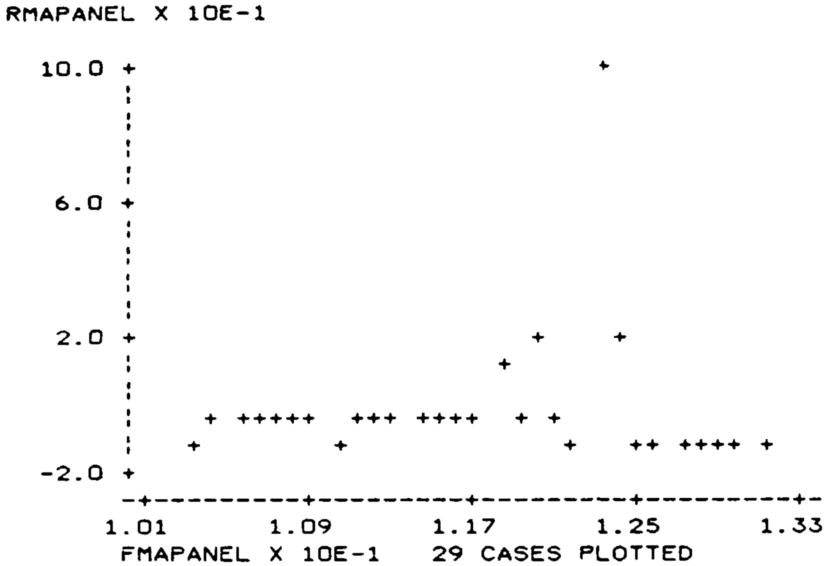
UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF MAPANEL

PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	STUDENT'S T	P
CONSTANT	1.0246E-01	7.9673E-02	1.29	0.2093
WEEK	9.8522E-04	4.6388E-03	0.21	0.8334

CASES INCLUDED	29	MISSING CASES	0
DEGREES OF FREEDOM	27		
OVERALL F	4.511E-02	P VALUE	0.8334
ADJUSTED R SQUARED	-0.0353		
R SQUARED	0.0017		
RESID. MEAN SQUARE	4.368E-02		

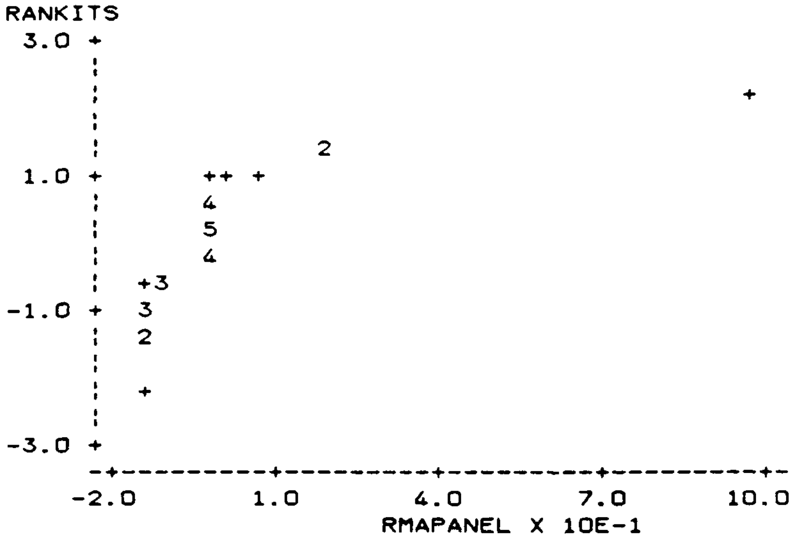
RMAPANEL VS FMAPANEL

(STATISTIX)



Assumption of equal variance was not apt.

RANKITS VS RMAPANEL



APPROX. WILK-SHAPIRO 0.4830 29 CASES PLOTTED

Assumption of normally distributed error terms was not apt.

PANEL (QUATTRO)

SUPPLY AIR REGRESSION ANALYSIS

PANEL SUPPLY AIR DRIFT IN %VOUT	REGRESSION VALUES
3	1.3131034
4.5	1.410197
5	1.5072906
0	1.6043842
0	1.7014778
0	1.7985714
0	1.895665
0	1.9927586
0	2.0898522
0	2.1869458
2.5	2.2840394
3.7	2.381133
2.8	2.4782266
3	2.5753202
5.4	2.6724138
3.6	2.7695074
4.5	2.866601
0	2.9636946
5.4	3.0607882
0	3.1578818
5.2	3.2549754
4.7	3.352069
0	3.4491626
0	3.5462562
5.2	3.6433498
5	3.7404433
4.5	3.8375369
5	3.9346305
4.5	4.0317241

PANEL SUPPLY AIR

Regression Output:

Constant	1.21601
Std Err of Y Est	2.134208
R Squared	0.134657
No. of Observations	29
Degrees of Freedom	27

X Coefficient(s)	0.097094
Std Err of Coef.	0.047368

MULTIPLE REGRESSION (STATISTIX)

```
WEEK       BUMAGUAGE BUMAPANEL MAPANEL   BUSAGUAGE BUSAPANEL SAPANEL   FBUMAGUAG
RBUMAGUAG FBUMAPANE RBUMAPANE RMAPANEL  FMAPANEL  RBUSAGUAG FBUSAGUAG FBUSAPANE
RBUSAPANE

17 variable(s), 29 cases, 29 selected. 103 free var(s), 32147 free items.
```

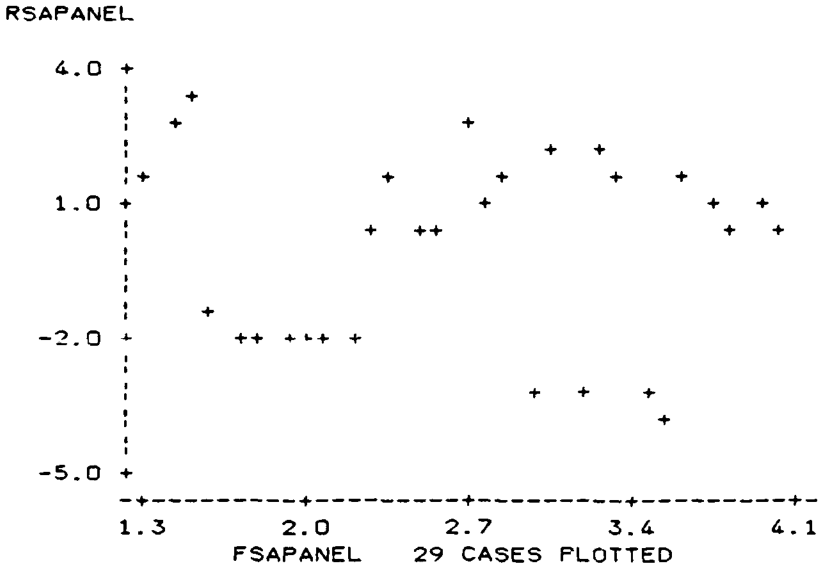
```
Enter regression model: Y = X1 X2 ... (WT = Var, NOCON).
You may enter ALL or use A .. Z syntax.
> SAPANEL=WEEK
```

UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF SAPANEL

PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	STUDENT'S T	P
CONSTANT	1.2160	8.1358E-01	1.49	0.1466
WEEK	9.7094E-02	4.7368E-02	2.05	0.0502

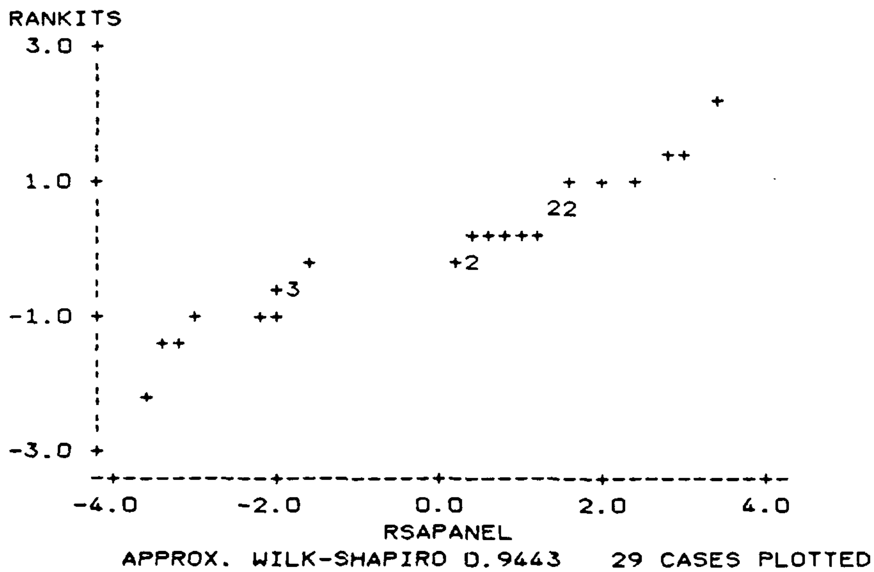
CASES INCLUDED	29	MISSING CASES	0
DEGREES OF FREEDOM	27		
OVERALL F	4.201	P VALUE	0.0502
ADJUSTED R SQUARED	0.1026		
R SQUARED	0.1347		
RESID. MEAN SQUARE	4.555		

RSAPANEL VS FSAPANEL (STATISTIX)



Assumption of equal variance was apt.

RANKITS VS RSAPANEL



Assumption of normally distributed error terms was apt.

Appendix E: Quantitative Regression Analysis

```
                         SAVE SYSTEM FILE        (STATISTIX)

OBS       PANEL     OBSP      MAGUPAN   MAPAPAN   SAGUPAN   SAPAPAN   FMAGUPAN
RMAGUPAN  FMAPAPAN  RMAPAPAN  FSAGUPAN  RSAGUPAN  FSAPAPAN  RSAPAPAN

15 variable(s), 58 cases, 58 selected. 105 free var(s), 31770 free items.
--------------------------------------------------------------------------------

Enter the output file name.
> C:\SX\THESIS1
```

OBS = Observation number or week number
PANEL = Ø when built-up system data was used, 1 when Panel data was used
OBSP = OBS data times PANEL number (Ø or 1)
MAGUPAN = Mixed air data on the built-up system measured by the gauge combined with mixed air data on the Panel system
MAPAPAN = Mixed air data on the built-up system measured by the Panel combined with mixed air data on the Panel system
SAGUPAN = Supply air data on the built-up system measured by the gauge combined with supply air data on the Panel system
SAPAPAN = Supply air data on the built-up system measured by the Panel combined with supply air data on the Panel system
FMAGUPAN = Fitted valves for MAGUPAN
RMAGUPAN = Residuals for MAGUPAN
FMAPAPAN = Fitted valves for MAPAPAN
RMAPAPAN = Residuals for MAPAPAN
FSAGUPAN = Fitted valves for SAGUPAN
RSAGUPAN = Residuals for SAGUPAN
FSAPAPAN = Fitted valves for SAPAPAN
RSAPAPAN = Residuals for SAPAPAN

VIEW DATA (STATISTIX)

CASE	OBS	PANEL	OBSP	MAGUPAN	MAPAPAN
1	1.0000	0.0000	0.0000	1.8000	0.8000
2	2.0000	1.0000	2.0000	0.0000	0.0000
3	3.0000	0.0000	0.0000	1.1000	0.3000
4	4.0000	1.0000	4.0000	0.1000	0.1000
5	5.0000	0.0000	0.0000	0.5000	5.5000
6	6.0000	1.0000	6.0000	0.1000	0.1000
7	7.0000	0.0000	0.0000	2.7000	3.0000
8	8.0000	1.0000	8.0000	0.1000	0.1000
9	9.0000	0.0000	0.0000	0.3000	0.3000
10	10.000	1.0000	10.000	0 1000	0.1000
11	11.000	0.0000	0.0000	0.3000	0.3000
12	12.000	1.0000	12.000	0.1000	0.1000
13	13.000	0.0000	0.0000	0.3000	0.3000
14	14.000	1.0000	14.000	0.1000	0.1000
15	15.000	0.0000	0.0000	0.0000	0.0000
16	16.000	1.0000	16.000	0.0000	0.0000
17	17.000	0.0000	0.0000	0.0000	0.0000
18	18.000	1.0000	18.000	0.1000	0.1000
19	19.000	0.0000	0.0000	0.0000	0.0000
20	20.000	1.0000	20.000	0.1000	0.1000
21	21.000	0.0000	0.0000	0.0000	0.0000
22	22.000	1.0000	22.000	0.1000	0.1000
23	23.000	0.0000	0.0000	0.0000	0.0000
24	24.000	1.0000	24.000	0.1000	0.1000
25	25.000	0.0000	0.0000	0.0000	0.0000
26	26.000	1.0000	26.000	0.1000	0.1000
27	27.000	0.0000	0.0000	0.0000	0.0000
28	28.000	1.0000	28.000	0.1000	0.1000
29	29.000	0.0000	0.0000	0.0000	0.0000
30	30.000	1.0000	30.000	0.1000	0.1000
31	31.000	0.0000	0.0000	0.0000	0.0000
32	32.000	1.0000	32.000	0.2000	0.2000
33	33.000	0.0000	0.0000	0.0000	0.0000
34	34.000	1.0000	34.000	0.1000	0.1000
35	35.000	0.0000	0.0000	0.0000	0.0000
36	36.000	1.0000	36.000	0.3000	0.3000
37	37.000	0.0000	0.0000	0.0000	0.0000
38	38.000	1.0000	38.000	0.1000	0.1000
39	39.000	0.0000	0.0000	0.0000	0.0000
40	40.000	1.0000	40.000	0.0000	0.0000
41	41.000	0.0000	0.0000	2.3000	4.0000
42	42.000	1.0000	42.000	1.1000	1.1000
43	43.000	0.0000	0.0000	0.0000	0.0000
44	44.000	1.0000	44.000	0.3000	0.3000
45	45.000	0.0000	0.0000	0.0000	0.0000
46	46.000	1.0000	46.000	0.0000	0.0000
47	47.000	0.0000	0.0000	0.0000	0.0000
48	48.000	1.0000	48.000	0.0000	0.0000
49	49.000	0.0000	0.0000	1.7000	0.0000
50	50.000	1.0000	50.000	0.0000	0.0000
51	51.000	0.0000	0.0000	5.0000	5.0000
52	52.000	1.0000	52.000	0.0000	0.0000
53	53.000	0.0000	0.0000	0.0000	0.0000
54	54.000	1.0000	54.000	0.0000	0.0000
55	55.000	0.0000	0.0000	0.0000	0.0000
56	56.000	1.0000	56.000	0.0000	0.0000
57	57.000	0.0000	0.0000	0.0000	0.0000
58	58.000	1.0000	58.000	0.0000	0.0000

MULTIPLE REGRESSION (STATISTIX)

```
OBS        PANEL      OBSP       MAGUPAN    MAPAPAN    SAGUPAN    SAPAPAN    FMAGUPAN
RMAGUPAN   FMAPAPAN   RMAPAPAN   FSAGUPAN   RSAGUPAN   FSAPAPAN   RSAPAPAN

15 variable(s), 58 cases, 58 selected. 105 free var(s), 31770 free items.
```

```
Enter regression model: Y = X1 X2 ... (WT = Var, NOCON).
You may enter ALL or use A .. Z syntax.
> MAGUPAN=OBS PANEL OBSP
```

UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF MAGUPAN

PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	STUDENT'S T	P
CONSTANT	5.3387E-01	3.1082E-01	1.72	0.0916
OBS	6.1576E-04	9.2834E-03	0.07	0.9474
PANEL	-4.3140E-01	4.4531E-01	-0.97	0.3370
OBSP	-1.2315E-04	1.3129E-02	-0.01	0.9926

```
CASES INCLUDED            58        MISSING CASES    0
DEGREES OF FREEDOM        54
OVERALL F              1.306        P VALUE     0.2818
ADJUSTED R SQUARED    0.0159
R SQUARED             0.0677
RESID. MEAN SQUARE   6.998E-01
```

(STATISTIX)

```
                    RMAGUPAN VS FMAGUPAN
RMAGUPAN

  5.0 +
      :                            +
      :
      :
      :
  3.0 +
      :
      :                           +
      :                            +
      :                           +
  1.0 +      +                     +
      :                           +
      :      3
      :     7*2                   4
      :                           6*
 -1.0 +
     -+---------+---------+---------+---------+-
     0.0       2.0       4.0       6.0       8.0
     FMAGUPAN X 10E-1   58 CASES PLOTTED
```

Assumption of equal variance was not apt.

```
                    RANKITS VS RMAGUPAN
RANKITS
  3.0 +
      :
      :                                 +
      :                    + +
      :             +  +2
  1.0 +           32
      :           8
      :          36
      :          9
      :        7 +
 -1.0 +        5
      :        4
      :        2
      :        +
      :
 -3.0 +
     -+---------+---------+---------+---------+-
    -2.0       0.0       2.0       4.0       6.0
                       RMAGUPAN
  APPROX. WILK-SHAPIRO 0.5901    58 CASES PLOTTED
```

Assumption of normally distributed error terms was not apt.

MULTIPLE REGRESSION (STATISTIX)

```
OBS         PANEL       OBSP        MAGUPAN     MAPAPAN     SAGUPAN     SAPAPAN     FMAGUPAN
RMAGUPAN    FMAPAPAN    RMAPAPAN    FSAGUPAN    RSAGUPAN    FSAPAPAN    RSAPAPAN

15 variable(s), 58 cases, 58 selected. 105 free var(s), 31770 free items.
```

```
Enter regression model: Y = X1 X2 ... (WT = Var, NOCON).
You may enter ALL or use A .. Z syntax.
> MAPAPAN=OBS PANEL OBSP
>
```

UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF MAPAPAN

PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	STUDENT'S T	P
CONSTANT	0.9810	4.1817E-01	2.35	0.0227
OBS	-1.0640E-02	1.2490E-02	-0.85	0.3980
PANEL	-8.7852E-01	5.9911E-01	-1.47	0.1483
OBSP	1.1133E-02	1.7663E-02	0.63	0.5312

CASES INCLUDED	58	MISSING CASES	0
DEGREES OF FREEDOM	54		
OVERALL F	1.419	P VALUE	0.2474
ADJUSTED R SQUARED	0.0216		
R SQUARED	0.0731		
RESID. MEAN SQUARE	1.267		

```
                   RMAPAPAN VS FMAPAPAN
RMAPAPAN

   5.0 +
       !               +               +
       !
       !
       !                  +
   3.0 +
       !
       !                              +
       !
       !
   1.0 +    +
       !
       !    3
       !   2*        ++                  +
       !              +++2 +2+2++2+ +++ +
  -1.0 +                           2
       -+---------+---------+---------+---------+-
       0.0       0.3       0.6       0.9       1.2
              FMAPAPAN   58 CASES PLOTTED
```

(STATISTIX)

Assumption of
equal variance
was not apt.

```
                   RANKITS VS RMAPAPAN
  RANKITS
   3.0 +
       !
       !                                 +
       !                           +     +
       !           2   +    +
   1.0 +          5
       !          8
       !         63
       !        45
       !       7+
  -1.0 +       5
       !      3+
       !      2
       !      +
       !
  -3.0 +
       -+---------+---------+---------+---------+-
      -2.0       0.0       2.0       4.0       6.0
                         RMAPAPAN
         APPROX. WILK-SHAPIRO 0.5403   58 CASES PLOTTED
```

Assumption of
normally distributed
error terms was not
apt.

VIEW DATA (STATISTIX)

CASE	OBS	PANEL	OBSP	SAGUPAN	SAPAPAN
1	1.0000	0.0000	0.0000	0.0000	0.0000
2	2.0000	1.0000	2.0000	0.3000	0.3000
3	3.0000	0.0000	0.0000	0.5000	6.2500
4	4.0000	1.0000	4.0000	0.4500	0.4500
5	5.0000	0.0000	0.0000	0.0000	0.0000
6	6.0000	1.0000	6.0000	0.5000	0.5000
7	7.0000	0.0000	0.0000	0.0000	0.0000
8	8.0000	1.0000	8.0000	0.0000	0.0000
9	9.0000	0.0000	0.0000	0.0000	0.0000
10	10.000	1.0000	10.000	0.0000	0.0000
11	11.000	0.0000	0.0000	0.0000	0.0000
12	12.000	1.0000	12.000	0.0000	0.0000
13	13.000	0.0000	0.0000	0.0000	0.0000
14	14.000	1.0000	14.000	0.0000	0.0000
15	15.000	0.0000	0.0000	0.0000	0.0000
16	16.000	1.0000	16.000	0.0000	0.0000
17	17.000	0.0000	0.0000	0.0000	0.0000
18	18.000	1.0000	18.000	0.0000	0.0000
19	19.000	0.0000	0.0000	0.0000	0.0000
20	20.000	1.0000	20.000	0.0000	0.0000
21	21.000	0.0000	0.0000	0.0000	0.0000
22	22.000	1.0000	22.000	0.2500	0.2500
23	23.000	0.0000	0.0000	0.0000	0.0000
24	24.000	1.0000	24.000	0.3700	0.3700
25	25.000	0.0000	0.0000	0.0000	0.0000
26	26.000	1.0000	26.000	0.2800	0.2800
27	27.000	0.0000	0.0000	0.0000	0.0000
28	28.000	1.0000	28.000	0.3000	0.3000
29	29.000	0.0000	0.0000	0.0000	0.0000
30	30.000	1.0000	30.000	0.5400	0.5400
31	31.000	0.0000	0.0000	0.0000	0.0000
32	32.000	1.0000	32.000	0.3600	0.3600
33	33.000	0.0000	0.0000	0.0000	0.0000
34	34.000	1.0000	34.000	0.4500	0.4500
35	35.000	0.0000	0.0000	0.0000	0.0000
36	36.000	1.0000	36.000	0.0000	0.0000
37	37.000	0.0000	0.0000	0.0000	0.0000
38	38.000	1.0000	38.000	0.5400	0.5400
39	39.000	0.0000	0.0000	0.0000	0.0000
40	40.000	1.0000	40.000	0.0000	0.0000
41	41.000	0.0000	0.0000	0.0000	0.0000
42	42.000	1.0000	42.000	0.5200	0.5200
43	43.000	0.0000	0.0000	0.0000	0.0000
44	44.000	1.0000	44.000	0.4700	0.4700
45	45.000	0.0000	0.0000	0.0000	0.0000
46	46.000	1.0000	46.000	0.0000	0.0000
47	47.000	0.0000	0.0000	0.0000	0.0000
48	48.000	1.0000	48.000	0.0000	0.0000
49	49.000	0.0000	0.0000	0.0000	0.0000
50	50.000	1.0000	50.000	0.5200	0.5200
51	51.000	0.0000	0.0000	0.0000	0.0000
52	52.000	1.0000	52.000	0.5000	0.5000
53	53.000	0.0000	0.0000	0.0000	0.0000
54	54.000	1.0000	54.000	0.4500	0.4500
55	55.000	0.0000	0.0000	0.0000	0.0000
56	56.000	1.0000	56.000	0.5000	0.5000
57	57.000	0.0000	0.0000	1.2000	3.4000
58	58.000	1.0000	58.000	0.4500	0.4500

MULTIPLE REGRESSION (STATISTIX)

```
OBS       PANEL     OBSP      MAGUPAN   MAPAPAN   SAGUPAN   SAPAPAN   FMAGUPAN
RMAGUPAN  FMAPAPAN  RMAPAPAN  FSAGUPAN  RSAGUPAN  FSAPAPAN  RSAPAPAN

15 variable(s), 58 cases, 58 selected. 105 free var(s), 31770 free items.
```

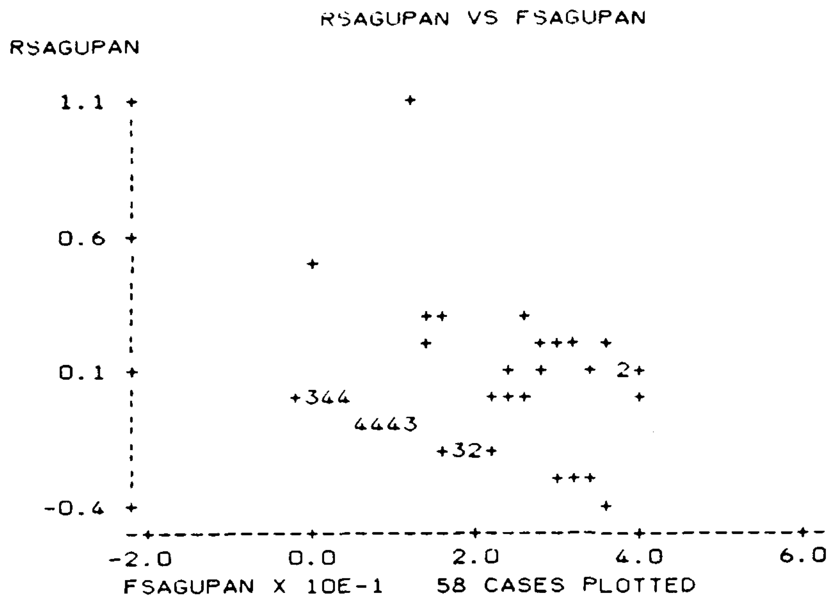
```
Enter regression model: Y = X1 X2 ... (WT = Var, NOCON).
You may enter ALL or use A .. Z syntax.
> SAGUPAN=OBS PANEL OBSP
>
```

UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF SAGUPAN

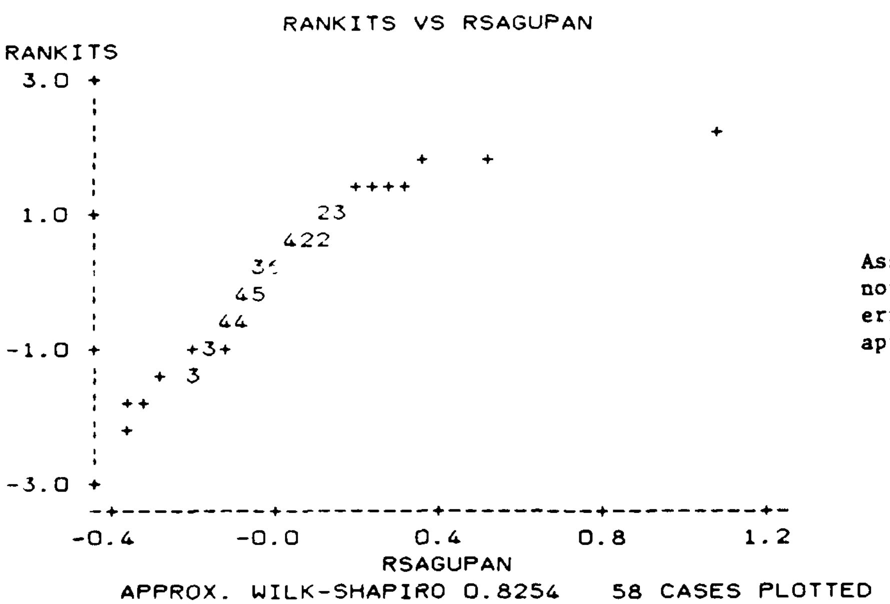
PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	STUDENT'S T	P
CONSTANT	-1.4951E-02	8.4121E-02	-0.18	0.8596
OBS	2.5369E-03	2.5125E-03	1.01	0.3171
PANEL	1.3655E-01	1.2052E-01	1.13	0.2622
OBSP	2.3177E-03	3.5532E-03	0.65	0.5170

CASES INCLUDED	58	MISSING CASES	0
DEGREES OF FREEDOM	54		
OVERALL F	5.688	P VALUE	0.0018
ADJUSTED R SQUARED	0.1979		
R SQUARED	0.2401		
RESID. MEAN SQUARE	5.126E-02		

(STATISTIX)



Assumption of equal variance was not apt.



Assumption of normally distributed error terms was not apt.

MULTIPLE REGRESSION (STATISTIX)

```
OBS        PANEL      OBSP       MAGUPAN    MAPAPAN    SAGUPAN    SAPAPAN    FMAGUPAN
RMAGUPAN   FMAPAPAN   RMAPAPAN   FSAGUPAN   RSAGUPAN   FSAPAPAN   RSAPAPAN

15 variable(s), 58 cases, 58 selected. 105 free var(s), 31770 free items.
```

```
Enter regression model: Y = X1 X2 ... (WT = Var, NOCON).
You may enter ALL or use A .. Z syntax.
> SAPAPAN=OBS PANEL OBSP
```

UNWEIGHTED LEAST SQUARES LINEAR REGRESSION OF SAPAPAN

PREDICTOR VARIABLES	COEFFICIENT	STD ERROR	STUDENT'S T	P
CONSTANT	5.7312E-01	3.5061E-01	1.63	0.1079
OBS	-8.2882E-03	1.0472E-02	-0.79	0.4321
PANEL	-4.5151E-01	5.0232E-01	-0.90	0.3727
OBSP	1.3143E-02	1.4809E-02	0.89	0.3788

```
CASES INCLUDED          58        MISSING CASES      0
DEGREES OF FREEDOM      54
OVERALL F          3.037E-01      P VALUE       0.8225
ADJUSTED R SQUARED -0.0380
R SQUARED           0.0166
RESID. MEAN SQUARE  8.904E-01
```

(STATISTIX)

```
                       RSAPAPAN VS FSAPAPAN
 RSAPAPAN

    7.0 +
        :
        :                            +
        :
        :
    4.0 +
        :      +
        :
        :
        :
    1.0 +
        :       2+    +++++++++
        :      ++3433322223222+2+++
        :                          +++
        :
   -2.0 +
        -+---------+---------+---------+---------+-
        0.0       2.0       4.0       6.0       8.0
        FSAPAPAN X 10E-1    58 CASES PLOTTED
```

Assumption of
equal variance
was not apt.

```
                       RANKITS VS RSAPAPAN
  RANKITS
    3.0 +
        :
        :                                   +
        :       +             +
        :      3+
    1.0 +      5
        :     62
        :     9
        :     9
        :   62
   -1.0 +   5
        :   4
        :  2
        :  +
        :
   -3.0 +
        -+---------+---------+---------+---------+-
       -1.0       1.0       3.0       5.0       7.0
                          RSAPAPAN
          APPROX. WILK-SHAPIRO 0.3866    58 CASES PLOTTED
```

Assumption of
normally distributed
error terms was not
apt.

Appendix F: Delphi Package Round 2

AFIT/LSG 6 Jan 89

Air Force Standard Control Panel

Dear:

Thank you for agreeing to participate in this AFIT Delphi survey. The purpose of this research is to determine the ease of design, installation and maintainability of the Air Force Standard Control Panel compared with other forms of heating, ventilating and air conditioning (HVAC) control systems. You were selected to participate in this important research because your experience and insight qualify you as an expert in the controls field with particular proficiency in the Air Force Control Panel. Your opinions will be combined with those of other experts in an effort to create the best possible control schemes for Air Force bases. Benefits to civilian industry and HVAC applications exist as well.

The attached Delphi survey constitutes the first written round but is actually the second round of the entire Delphi process. As you remember, the first round of the entire process was conducted during the telephone conversation we had previously. The attached survey solicits your personal professional opinions in a number of areas. To assist in this research, please complete the survey and return it in the enclosed envelope within 10 days. If this 10-day time period is not sufficient, please notify me. Since my purpose is to obtain complete, accurate information, I will gladly compromise the response period to achieve that purpose. As soon as all the responses are compiled, a second Delphi survey (round three) will be mailed to you. Be assured, your responses to both surveys will remain anonymous.

I am very excited about the responses I received during the first (telephone) round. The consolidated information from round one is included in the attached survey. Some of the questions could not be answered by the experts during the time the interview was conducted on the phone. Since the first (telephone) round was primarily exploratory in nature, neither the purpose nor the results of the research will be impacted by the missing responses. On the contrary, the responses contributed greatly to the direction of the research. Additionally, those experts assured me complete responses would be made during the second round. I look forward to all the information I expect to obtain during the two written rounds (rounds two and three).

I must mention that my solicitation of your opinions can not be construed as an obligation on my part or on the part of the Air Force to reimburse or compensate you for your time or expenses. Your efforts can only be interpreted as voluntary contributions to the research.

Your comments, suggestions, and ideas regarding this research are welcome and encouraged. If you have any questions about this survey, please call me at 513-255-4437/4552 or AV 785-4437. Thank you for making time to share your expertise.

KEVIN E. RUMSEY, Capt, USAF
Graduate Engineering Mgt Student

3 Atch
1. Delphi Survey
2. ETL 83-1, Change 1
3. Return Envelope

Round Two Delphi Survey

1. As a reminder, round one of this Delphi process was conducted via a telephone interview. The responses to round one are provided in this survey immediately following the appropriate question. In each response, attempts were made to include as much of the information you provided as possible. However, if portions of the information could reveal the identity of the expert, that portion was deleted prior to recording and disseminating the responses in this survey. Additionally, the order of appearance of the responses was changed for every question thereby eliminating any possibility of piecing together tne identity of an expert by a future reader of this research. This is round two, the first written round.

2. The objective of this survey is to obtain expert opinions concerning the design, installation and maintainability of the Air Force Standard Control Panel as described in Engineering Technical Letter 83-1 (ETL 83-1), Change 1. A copy of ETL 83-1, Change 1 is provided for your reference.

3. General Comments:

a. The subject areas covered in this questionnaire are not meant to be complete or exhaustive. Instead, the coverage is designed to stimulate your thinking.

b. Your participation and honest opinions are key to the success of this research project. <u>There are no right or wrong answers</u>. Therefore, all your ideas and brainstorming comments should be included. Feel free to consult your subordinates, superiors or co-workers. In the third round of questioning, ideas presented may spark additional comments by other participants.

c. Three rounds (one by telephone) are needed to ensure all opinions are disseminated to all experts. After this round, all responses will be compiled and given back to you to begin the next (final) round. Additionally, you will be provided an executive summary of this research after it is completed.

d. The questionnaire is divided into various topic areas. Some questions require that you circle one of the answers provided. Others solicit your personal comments. Feel free to provide comments at any point and for any question. <u>Remember, complete anonymity will be enforced</u>.

Atch 1

4. Definitions: Some of the questions address aspects of the panel during a particular phase of the panel's life cycle. In some cases, the time periods of the phases may overlap. These phases are defined as follows;

a. Development--The portion of time from the panel's inception through manufacturing.

b. Design--The design phase of an Air Force or civilian construction project. The design phase includes the time devoted to designing the mechanical portion of the project incorporating an Air Force Standard Panel. It also refers to time spent planning an in-house work order in Civil Engineering.

c. Installation--The phase of construction during which the panel is installed, connected to sensors and controlled devices, calibrated and tested.

d. Operations and Maintenance--The time period during which the panel is functioning properly (e.g., maintaining setpoint) without recalibration.

5. Specific Instructions:

a. When a question calls for an answer among a group of choices, please circle the response(s) which most accurately reflect(s) your experience in that area.

b. Since the responses you give are considered expert opinions, please provide rationale for your answers where appropriate, especially for areas where you feel strongly. Add any illustrations, examples or experiences you have had that will help the other participants understand your responses. Feel free to attach any additional pages of pictures, drawings or data you feel necessary to explain your point. Be assured, any information in these examples which attributes the material to a particular expert or employing organization will be removed before the example is disseminated in the next round.

c. If particular questions do not directly apply to you, please feel free to consult co-workers who may have had more experience in the particular area. Consulting others does not infringe on or downgrade your title as an expert. On the contrary, an expert does not always know everything about a particular subject. An expert does, however, know where to search for the information, and has the self-confidence to solicit information from others where his or her own knowledge is incomplete.

d. The last page of the survey is provided for any additional comments you have about the study.

e. If you have any questions about the research or the survey, please call Capt Kevin Rumsey, 513-255-4437/4552 or AV 785-4437/4552.

THANKS AGAIN FOR YOUR SINCERE PARTICIPATION.

AREA 1: YOUR EXPERIENCE

The ranges of experience were discussed and recorded by hand during the telephone interview. However, to ensure accuracy and completeness, please provide it again.

The experience of the personnel interviewed during the first round varied from panel development through operations and maintenance. The impact of this information on the research is to guarantee all phases of the life cycle of the panel are looked at, analyzed, and compared with similar phases of other control systems.

Question 1.

-What phase(s) of the life of the Control Panel(s) have you been involved in and what was your function during that phase? Also, how long did you work with the panel(s) during each phase? (The second question was not asked during round one.)
(More than one answer is possible.)

ROUND ONE RESPONSES

One expert works in a supervisory function over the technicians who operate and maintain the panel.

One expert selected the panel for the particular application, was involved in the design, and supervises technicians who maintain the panel.

One expert was involved in the development of the panel and is consulted on design, installation, and operations and maintenance applications.

One expert is involved in installations and operations and maintenance.

One expert got involved after the Construction Engineering Research Lab (CERL) wrote the controller specification and continues to be involved in design and installation applications and operations and maintenance.

One expert is involved in design, installation, and operations and maintenance.

One expert worked with the panel from its inception through operations and maintenance.

One expert worked with the panel in the design, installation, and operations and maintenance phases.

ROUND TWO RESPONSES (PLEASE WRITE YOUR RESPONSE HERE.)

PHASE OF TIME	FUNCTION	LENGTH
DEVELOPMENT		
DESIGN		
INSTALLATION		
OPERATIONS AND MAINTENANCE		

AREA 2: TYPE OF PANEL

During the telephone interview, only the Hot Water Temperature Control (#4 below), Variable Air Volume (VAV) Temperature Control (#3 below), Static Pressure Control for Inlet Vane Damper System (#2 below), and Multizone Control (#8 below) panels were reported in operation (see round one responses below). All eight types have been designed and could be manufactured. Although this question was asked during round one, it is repeated here to ensure information accuracy and include possible new information.

Question 2

-What types of panels have you worked with during any phase of panel life, inception through operations and maintenance? (More than one answer is possible.)

1. Static Pressure Control Panel for Fan Speed Control (FSC) System

2. Static Pressure Control Panel for Inlet Vane Damper (IVD) System

3. Variable Air Volume (VAV) Temperature Control Panel

4. Hot Water Temperature Control Panel

5. Temperature Control Panel for Single Zone System with One Controller

6. Temperature Control Panel for Single Zone System with Cascade Control

7. Temperature and Humidity Control Panel for Single Zone System

8. Multizone Control Panel

****End of formal panel types.****

9. A custom-built panel designed, constructed and installed according to ETL 83-1, Change 1. (Note: If you select this type of panel as your response, please describe the function, application and construction of your panel.)

ROUND ONE RESPONSES

Two experts have worked with panels 2,3,4 and 8 from inception through operations and panels 1,5,6 and 7 from inception through design.

One expert worked with panels 2,3,4 and 8 from design through operations and panels 1,5,6 and 7 in design only.

One expert worked with a custom-built panel (#9 above) which performed multiple functions. These functions were not described.

One expert worked with panels 2,3,4 and 8 with some modifications for particular applications from design through operations and panels 1,5,6, and 7 in design only.

One expert worked with panels 2 and 3 during installation and operations and maintenance.

Two experts could not specify what type of panel was worked with during the telephone conversation time period.

ROUND TWO--YOUR RESPONSES

AREA 2: **TYPE OF PANEL (Continued)**

Question 3

-Understanding that the panel may be used as part of a retrofit project as well as new HVAC projects, what types of sensors, actuators, and controllers (electronic, pneumatic, DDC) does (do) the panel(s) from your responses to question 2 work with?

ROUND ONE RESPONSES

Two experts could not specify what components their panels worked with during the telephone conversation time period.

Six experts' panels were used with electronic sensors and pneumatic actuators according to ETL 83-1, Change 1.

ROUND TWO--YOUR RESPONSES

AREA 3: **DESIGN PHASE**

During the design phase, areas of concern are (1) the panel's adaptability to the overall HVAC system under design compared to other control systems and (2) the involvement of the architect/engineer if applicable.

Question 4

-What were your experiences with the Air Force Standard Panel during the design of the entire HVAC system? Additionally, what type of system did it replace, what alternative control systems were investigated, and what caused you to select a panel for your application? (The second question was not asked during round one.) (If this is not applicable to you, please feel free to consult co-workers who may have had more experience. If this is done, please record the individual's name, job title, and experience with the panel in a format similar to survey question 1. Remember, the research is an effort to obtain as much information as possible and disseminate it to all the experts.)

ROUND ONE RESPONSES

One expert indicated the Corps of Engineers have the panel on the AutoCAD design software package and the specification verbiage is in the HVAC Technical Specification manual. This combination allows for easy design.

One expert mentioned that, although the specifications or statements of work in a project may call for an Air Force Standard Control Panel, architects/engineers and contractors continue to make value engineering proposals for a different control scheme. Many of these proposals are being accepted at base level. This expert also mentioned that the Army is using a similar concept in their control panels. However, instead of using analog controllers, their panels will use industrial-grade, single-loop microprocessor controllers. Each microprocessor can be programmed to control any type of loop--hot water control, VAV, etc. The advantage of this scheme is that only one panel is required, regardless of the loops involved in the HVAC system, because many microprocessors can fit into a small space. With the AF panel, more control loops mean more panels.

One expert indicated that designers have a general reluctance to sign off on the control system design because it is not truly their own. This expert also believes industrial-grade components are not required, only commercial grade. This expert does not favor the particular specification method used in the HVAC Technical

Specifications. Instead, this expert believes a performance specification would yield better products.

One expert believes many of the panel functions could be removed from the panel specifications and be performed by the base energy monitoring and control system (EMCS) instead.

Two experts did not have any experience in the design phase and were not able to consult the appropriate personnel during the telephone conversation time period.

One expert had little experience in the design phase, but remembered no problems applying the panel design to the HVAC application.

One expert favored design of control systems which included an AF Standard Panel over other control schemes because of the availability of the Standard HVAC Technical Specifications. Additionally, because the panel incorporates a single loop concept, it is easier for the designer to understand due to its similarity to pneumatic controls. However, the maintenance and diagnostic features are difficult for many designers because it is a new concept.

ROUND TWO--YOUR RESPONSES
(Feel free to comment on any of the statements above.)

AREA 4: **INSTALLATION PHASE**

During the installation phase, some areas of concern are the ease of installation (mounting and connecting to sensors, controlled devices and EMCS), calibration, training, and documentation. Please relate documentation to installation, calibration, and training where applicable.

Question 5

-What were your experiences with the Air Force Standard Panel during the installation of the entire HVAC system? (If this is not applicable to you, please feel free to consult co-workers who may have had more experience. If this is done, please record the individual's name, job title, and experience with the panel in a format similar to survey question 1. Remember the research is an effort to obtain as much information as possible and disseminate it to all the experts.)

ROUND ONE RESPONSES

One expert indicated the panel is easy to install since only a few wires are required for sensor connection. Training is required for the diagnostics and calibration. If CERL input is used from the Technical Specifications, calibration and operation are simple.

One expert was concerned with the additional cost of the panel. This expert found a higher first cost for electronic components, such as those in the panel, as opposed to pneumatic components in a built-up system. This expert estimates a 20-30% cost difference in components alone. This does not include diagnostic features and component housing costs.

One expert encountered no problems during installation and calibration after an explanation of the function of each component was given to the individuals calibrating the system. However, if explanations were not given, the panel has an intimidation factor which may inhibit proper installation and calibration.

One expert encountered no problems during panel installation.

One expert was not involved in panel installation and was not able to consult those involved in the telephone conversation time period.

One expert found "real smooth" installations.

One expert found the installation and calibration procedures too complicated for technicians to understand. This expert believes more training is required for these technicians in electronic areas.

One expert found incorrect installation procedures and calibration at a particular location. This system did not function properly due primarily to the installation of sensors which were incompatible with the panel controllers, improper design which allowed for a variation in component installation, components outside the panel being incorrectly connected and controllers calibrated with too narrow proportional band settings.

<u>ROUND TWO--YOUR RESPONSES</u>
(Feel free to comment on any of the above-made statements.)

AREA 5: OPERATIONS AND MAINTENANCE

Maintenance of the entire HVAC system, including the controls portion, is a major concern of the Air Force. Two important aspects of maintainability include (1) an ability to diagnose the HVAC system from the controls and (2) the reliability of the components of the control system themselves. Diagnostic capability includes the intimidation factor vs the panel's "seductiveness" to be used by the technician. Long-term reliability is difficult to assess since the panel has only been mandatory since July 1987, but please relay whatever information you have, including frequency of replacement and/or repair of components and frequency of calibration.

Question 6

-What were your experiences with the operations and maintenance of the Air Force Standard Panel? Please state, when making subjective statements, if the judgment is relative to pneumatic, electronic, DDC systems, or an ideal system which is yet to be developed or implemented (If this is not applicable to you, please feel free to consult co-workers who may have had more experience. If this is done, please record the individual's name, job title, and experience with the panel in a format similar to survey question 1. Remember, the research is an effort to obtain as much information as possible and disseminate it to all the experts.)

ROUND ONE RESPONSES

Concerning maintenance, one expert indicated one panel had trouble with two E/P transducers and one reset module. However, no controllers required replacement. This expert also found 75-80% of the technicians were afraid to become familiar with the knobs and buttons composing the panel's diagnostic features. Once these features had been explained to them, the fear of touching the panel dissipated.

One expert believes many of the panel functions could be performed by EMCS. This expert also believes the panels are too complicated for many technicians and the Air Force training is not sufficient for the complication level as compared to pneumatic controls. The gauges are not used because the technicians don't understand their functions. Instead, technicians are used to tweaking components in an effort to solve a problem, not analyzing it using diagnostics. Training is difficult at base level, especially on bases which use the zone concept. Although the panels are too complicated, this expert believes standardization is a step in the right direction.

One expert cited a situation during which the panel was used to expose deficiencies in an HVAC system.

One expert believes the hidden costs in electronic components are due to the inability of the technicians to properly troubleshoot and calibrate electronic systems. This inability, coupled with the problems with electronic components due to heat generation, results in a shorter life for electronic components (12-15 years) compared to pneumatic components (20-22 years). This expert believes if technicians familiar with only pneumatic systems are expected to work with the electronic components in the panel without proper training, damaged or bypassed components will result. This expert believes the hybrid (electronic controllers and sensors with pneumatic actuators) system mandated by ETL 83-1, Change 1 is a step in the right direction, but more training is required and it may necessitate hiring technicians with a higher level of education. Additionally, this expert is not convinced the Air Force receives the hybrid system it asks for in every case.

One expert believes less maintenance trouble and customer complaints result from the panel than from built-up or separate component systems.

One expert found many problems with controllers in two different types of panels. Once the controllers were replaced, no further problems were experienced.

Two experts found no problems with their panels' operation to date.

<u>ROUND TWO--YOUR RESPONSES</u>
(Feel free to comment on any of the above-made statements.)

AREA 6: **FUTURE USE**

Question 7

Considering all the pros and cons of your Air Force Standard Panel installation, would you install another one? Why or why not?

<u>ROUND ONE RESPONSES</u>

This question was not asked during the first round of the survey, hence, no responses are provided.

<u>ROUND TWO--YOUR RESPONSES</u>

AREA 7: ADDITIONAL COMMENTS

Please provide any additional comments you may have about either the Air Force Standard Control Panel or the Delphi technique employed to solicit and consolidate expert opinions. Include, if possible, other sources of potential experts in this area. These individuals may be included in the final (third) round of this survey or be provided as sources for future research in this area.

Thank you for your participation and sharing your opinions. Please mail this survey within ten days of receipt to AFIT/LSG (Bldg 641), Wright-Patterson AFB, OH 45433-6583. A stamped, pre-addressed envelope is enclosed for your convenience.

ROUND ONE RESPONSES

One expert mentioned work done by the US Navy using control systems composed of DDC boards. The primary problem with these systems was the inability of DDC controls to talk to each other due to the lack of a common language.

Four experts were not able to make further comments during the telephone conversation time period.

One expert mentioned the possible replacement of the single loop analog controllers with single loop microprocessors. This expert believes that, due to the advantage of microprocessors in space, i.e., only one panel required to house many controller functions, microprocessors are the wave of the future in standard panels.

One expert wishes the Air Force had more panels installed because the panels are so simple to maintain, have good control, and don't require the technicians to know so many systems.

One expert predicts a company will be able to make the panel very cheaply and underbid the "good" companies for business. When this happens, the Air Force will end up with junk. To avoid this, the expert suggests the Air Force write a super performance specification.

Appendix G: Delphi Package Round 3

28 Mar 89

Dear :

Thank you again for agreeing to participate in this AFIT Delphi survey. As a reminder, this package is the third of three rounds of research which will be used to determine the ease of design, installation and maintainability of the Air Force Standard Control Panel compared with other forms of heating, ventilating and air conditioning (HVAC) control systems. You were selected to participate in this important research because your experience and insight qualify you as an expert in the controls field with particular proficiency in the Air Force Control Panel. Your opinions will be combined with those of other experts in an effort to create the best possible control schemes for Air Force bases. Benefits to civilian industry and HVAC applications exist as well.

I was very excited about the responses I received during round two, the first written round. As you remember, the first round of the entire process was conducted during the telephone conversation we had *previously* and the second round was recently completed via the mail. The attached survey contains the same questions you saw during round two. However, there are two differences in how I am asking you to respond to the survey. These differences are the objective of the third round and the questions for which answers are required.

First, I have compiled all your answers to rounds one and two directly after the appropriate question. Using these answers, my objective in the third round is to obtain your opinions on what other experts have said about the panel. This is not simply a reiteration of round two, during which you responded with your experience with the panel. This time, I am interested in your professional judgment about what the other experts have said. Of course, if you have additional information on the panel, I will welcome it. But, the primary purpose of this round is to disseminate all the information collected so far and get opinions on it. Hopefully, this will mean less work for you and the survey will not consume as much of your time.

The second difference is that you are not required to reaccomplish answers to questions one and two. These questions were to be sure the experts had experience in all aspects of the panel. As you will see, your experience is more than adequate.

To assist in this last round, please complete the survey and return it in the enclosed envelope within 10 days. If this 10-day time period is not sufficient, please notify me. Since my purpose is still to obtain complete, accurate information, I will compromise the response period to achieve that purpose. However, my academic schedule for this research is somewhat more stringent this term. Therefore, please call me if you cannot meet the 10-day deadline. As with rounds one and two, your responses to this survey will remain anonymous.

I must mention again that my solicitation of your opinions cannot be construed as an obligation on my part or on the part of the Air Force to reimburse or compensate you for your time or expenses. Your efforts can only be interpreted as voluntary contributions to the research.

Your comments, suggestions, and ideas regarding this research are welcome and encouraged. If you have any questions about this survey, please call me at (513) 255-4437/4552 or AV 785-4437. Thank you for making time to share your expertise.

KEVIN E. RUMSEY, Capt, USAF
Graduate Engineering Mgt Student

3 Atch
1. Delphi Survey
2. ETL 83-1, Change 1
3. Return Envelope

Round Three Delphi Survey

1. As a reminder, round one of this Delphi process was conducted via a telephone interview and round two was conducted through the mail. The responses to rounds one and two are provided in this survey immediately following the appropriate question. It is the responses from experts which are the subject of discussion for this round.

2. Round three is NOT simply a repetition of round two. This round is designed to 1) show the experts the amount of agreement in each question area and 2) solicit your comments in the areas where there is not agreement. Disagreement by one or more experts does not mean anyone is right or wrong. We are all aware of the individual differences in people as well as HVAC systems. The purpose of disseminating this information is to let all the experts know what others think of the Standard Panel, bring any existing problems up to the surface and disperse the information which might bring about a solution.

3. In each response, attempts were made to include as much of the information you provided as possible. However, if portions of the information could reveal the identity of the expert, that portion was deleted prior to recording and disseminating the responses in this survey. Additionally, the order of appearance of the responses was changed for every question, thereby eliminating any possibility of piecing together the identity of an expert by a future reader of this research.

4. The objective of this survey is to obtain expert opinions concerning the design, installation and maintainability of the Air Force Standard Control Panel as described in Engineering Technical Letter (ETL) 83-1, Change 1. A copy of ETL 83-1, Change 1 is provided for your reference.

5. General Comments:

a. The subject areas covered in this questionnaire are not meant to be complete or exhaustive. Instead, the coverage is designed to stimulate your thinking. I anticipate that the responses from other experts will spark some reactions from you as well.

b. Your participation and honest opinions are key to the success of this research project. There are no right or wrong answers. Therefore, all your ideas and brainstorming comments should be included. Feel free to consult your subordinates, superiors or co-workers.

Atch 1

c. You will be provided an executive summary of this research after it is completed.

d. The questionnaire is divided into various topic areas. Feel free to provide comments at any point and for any question. Remember, complete anonymity will be enforced.

6. Definitions: Some of the questions address aspects of the panel during a particular phase of the panel's life cycle. In some cases, the time periods of the phases may overlap. These phases are defined as follows;

a. Development--The portion of time from the panel's inception through manufacturing.

b. Design--The design phase of an Air Force or civilian construction project. The design phase includes the time devoted to designing the mechanical portion of the project incorporating an Air Force Standard Panel. It also refers to time spent planning an in-house work order in Civil Engineering.

c. Installation--The phase of construction during which the panel is installed, connected to sensors and controlled devices, calibrated and tested.

d. Operations and Maintenance--The time period during which the panel is functioning properly (e.g., maintaining setpoint) without recalibration.

7. Specific Instructions:

a. Since the responses you give are considered expert opinions, please provide rationale for your answers where appropriate, especially for areas where you feel strongly. Add any illustrations, examples or experiences you have had that will help the other participants understand your responses. Feel free to attach any additional pages of pictures, drawings or data you feel necessary to explain your point. Be assured, any information in these examples which attributes the material to a particular expert or employing organization will be removed before the example is disseminated in the next round.

b. If particular questions do not directly apply to you, please feel free to consult co-workers who may have had more experience in the particular area. Consulting others does not infringe on or downgrade your title as an expert. On the contrary, an expert does not always know everything about a particular subject. An expert does, however, know where to search for the information, and has the self-confidence to solicit information from others where his or her own knowledge is incomplete.

c. The last page of the survey is provided for any additional comments you have about the study.

d. If you have any questions about the research or the survey, please call Capt Kevin Rumsey, (513) 255-4437/4552 or AV 785-4437/4552.

THANKS AGAIN FOR YOUR SINCERE PARTICIPATION.

AREA 1: YOUR EXPERIENCE

YOU ARE NOT REQUIRED TO ANSWER THIS QUESTION AGAIN DURING THE THIRD ROUND.

The ranges of experience were discussed and recorded by hand during the telephone interview (round one) and recorded from your written responses for round two. The information obtained indicates a wide variety of expertise with extensive experience--factors which greatly increase the validity of the research results. The impact of this information on the research is to guarantee all phases of the life cycle of the panel are looked at, analyzed, and compared with similar phases of other control systems.

Question 1.

-What phase(s) of the life of the Control Panel(s) have you been involved in and what was your function during that phase? Also, how long did you work with the panel(s) during each phase? (The second question was not asked during round one.)
(More than one answer is possible.)

ROUND ONE RESPONSES

One expert works in a supervisory function over the technicians who operate and maintain the panel.

One expert selected the panel for the particular application, was involved in the design, and supervises technicians who maintain the panel.

One expert was involved in the development of the panel and is consulted on design, installation, and operations and maintenance applications.

One expert is involved in installation and operations and maintenance.

One expert got involved after the Construction Engineering Research Lab (CERL) wrote the controller specification and continues to be involved in design and installation applications and operations and maintenance.

One expert is involved in design, installation, and operations and maintenance.

One expert worked with the panel from its inception through operations and maintenance.

One expert worked with the panel in the design, installation, and operations and maintenance phases.

ROUND TWO RESPONSES

Two experts have been involved with the panel from development, which included review of the Design Instructions and Technical Specifications and testing, through present-day installations and operations and maintenance applications for which they provide consultation. One of these experts has worked with the panel for five years, the other for over three years.

One expert provided technical assistance for three weeks during the installation of the panel and was kept informed about any problems which occurred during the operations and maintenance phase of the same panel, which has been functioning for about six months.

One expert hired the consulting engineering company which specified the Standard Panel.

One expert has been involved with the panel for two years. He was concerned with marketing, applications selections during the design phase, supervision during installations, and training and supervision during operations and maintenance.

One expert supervised HVAC, structural and electrical personnel in facility and equipment operations and maintenance for five years and was involved with the panel for about a year.

NO RESPONSES REQUIRED FOR ROUND THREE.

AREA 2: TYPE OF PANEL

YOU ARE NOT REQUIRED TO ANSWER THIS QUESTION AGAIN DURING THE THIRD ROUND.

During the telephone interview, only the Hot Water Temperature Control (#4 below), Variable Air Volume (VAV) Temperature Control (#3 below), Static Pressure Control for Inlet Vane Damper System (#2 below), and Multizone Control (#8 below) Panels were reported in operation (see round one responses below). All eight types have been designed and could be manufactured. Although this question was asked during round one, it is repeated here to ensure information accuracy and include possible new information.

Question 2

-What types of panels have you worked with during any phase of panel life, inception through operations and maintenance? (More than one answer is possible.)

1. Static Pressure Control Panel for Fan Speed Control (FSC) System

2. Static Pressure Control Panel for Inlet Vane Damper (IVD) System

3. Variable Air Volume (VAV) Temperature Control Panel

4. Hot Water Temperature Control Panel

5. Temperature Control Panel for Single Zone System with One Controller

6. Temperature Control Panel for Single Zone System with Cascade Control

7. Temperature and Humidity Control Panel for Single Zone System

8. Multizone Control Panel

****End of formal panel types.****

9. A custom-built panel designed, constructed and installed according to ETL 83-1, Change 1. (Note: If you select this type of panel as your response, please describe the function, application and construction of your panel.)

ROUND ONE RESPONSES

Two experts have worked with panels 2,3,4 and 8 from inception through operations and panels 1,5,6 and 7 from inception through design.

One expert worked with panels 2,3,4 and 8 from design through operations and panels 1,5,6 and 7 in design only.

One expert worked with a custom-built panel (#9 above) which performed multiple functions. These functions were not described.

One expert worked with panels 2,3,4 and 8 with some modifications for particular applications from design through operations and Panels 1,5,6, and 7 in design only.

One expert worked with panels 2 and 3 during installation and operations and maintenance.

Two experts could not specify what type of panel was worked with during the telephone conversation time period.

ROUND TWO RESPONSES

PANEL TYPE	NUMBER OF EXPERTS WHO HAVE WORKED ON THE PANEL		PHASE DURING WHICH THE EXPERT WORKED ON THE PARTICULAR PANEL
1			
	1	-	development
	3	-	design
	4	-	installation
	5	-	operations and maintenance
2			
	1	-	development
	2	-	design
	1	-	installation
	3	-	operations and maintenance
3			
	1	-	development
	2	-	design
	3	-	installation
	4	-	operations and maintenance
4			
	1	-	development
	2	-	design
	2	-	installation
	3	-	operations and maintenance

5			
	1	-	development
	2	-	design
	1	-	installation
	3	-	operations and maintenance
6			
	1	-	development
	1	-	design
7			
	1	-	development
	1	-	design
	2	-	operations and maintenance
8			
	1	-	development
	2	-	design
	2	-	installation
	3	-	operations and maintenance
9			
	1	-	design
	1	-	installation
	1	-	operations and maintenance

Additional Comments.

One expert had "...seen projects requiring panel 6 but have always recommended using a panel similar to 5 in its place...[This expert's] type 9 panels have all been similar to the Standard Panels with additional functions added by the designer to make them compatible with the mechanical systems, i.e., building pressure control, fan H-O-A switches, electronic output to actuators for small projects, etc. The "special" panels usually add more cost to the project than their true value provides, i.e., new engineering, drafting and special assembly costs just to add H-O-A switches is not cost effective."

<u>NO RESPONSES REQUIRED FOR ROUND THREE</u>.

AREA 2: **TYPE OF PANEL** (Continued)

Question 3

-Understanding that the Panel may be used as part of a retrofit project as well as new HVAC projects, what types of sensors, actuators, and controllers (electronic, pneumatic, DDC) does (do) the panel(s) from your responses to question 2 work with?

<u>ROUND ONE RESPONSES</u>

Two experts could not specify what components their panels worked with during the telephone conversation time period.

Six experts' panels were used with electronic sensors and pneumatic actuators according to ETL 83-1, Change 1.

<u>ROUND TWO RESPONSES</u>

All panels from all experts worked with electronic PI controllers, RTD temperature sensors and/or differential pressure transmitters (for static pressure, fan speed control or humidity control). Also, the panels used pneumatic actuators on most projects, but electronic actuators were used on small projects where an air compressor is not cost effective.

<u>NO RESPONSES REQUIRED FOR ROUND THREE SINCE THERE WAS 100% AGREEMENT DURING ROUND TWO.</u>

AREA 3: DESIGN PHASE

During the design phase, areas of concern are (1) the panel's adaptability to the overall HVAC system under design compared to other control systems and (2) the involvement of the architect/engineer if applicable.

Question 4

-What were your experiences with the Air Force Standard Panel during the design of the entire HVAC system? Additionally, what type of system did it replace, what alternative control systems were investigated, and what caused you to select a panel for your application? (The second question was not asked during round one.) (If this is not applicable to you, please feel free to consult co-workers who may have had more experience. If this is done, please record the individual's name, job title, and experience with the panel in a format similar to survey question 1. Remember, the research is an effort to obtain as much information as possible and disseminate it to all the experts.)

ROUND ONE RESPONSES

One expert indicated the Corps of Engineers have the panel on the AutoCAD design software package and the specification verbiage is in the HVAC Technical Specification manual. This combination allows for easy design.

One expert mentioned that, although the specifications or statements of work in a project may call for an Air Force Standard Control Panel, architects/engineers and contractors continue to make value engineering proposals for a different control scheme. Many of these proposals are being accepted at base level. This expert also mentioned that the Army is using a similar concept in their Control Panels. However, instead of using analog controllers, their panels will use industrial-grade, single-loop microprocessor controllers. Each microprocessor can be programmed to control any type of loop--hot water control, VAV, etc. The advantage of this scheme is that only one panel is required, regardless of the loops involved in the HVAC system, because many microprocessors can fit into a small space. With the AF Panel, more control loops mean more panels.

One expert indicated that designers have a general reluctance to sign off on the control system design because it is not truly their own. This expert also believes industrial-grade components are not required, only commercial grade. This expert does not favor the particular specification method used in the HVAC Technical

Specifications. Instead, this expert believes a performance specification would yield better products.

One expert believes many of the panel functions could be removed from the panel specifications and be performed by the base energy monitoring and control system (EMCS) instead.

Two experts did not have any experience in the design phase and were not able to consult the appropriate personnel during the telephone conversation time period.

One expert had little experience in the design phase, but remembered no problems applying the panel design to the HVAC application.

One expert favored design of control systems which included an AF Standard Panel over other control schemes because of the availability of the Standard HVAC Technical Specifications. Additionally, because the panel incorporates a single loop concept, it is easier for the designer to understand due to its similarity to pneumatic controls. However, the maintenance and diagnostic features are difficult for many designers because it is a new concept.

ROUND TWO RESPONSES

One expert "...does not believe `standard specifications' are the way to go. A standard spec will always be a compromise in performance. Every building is different and requires specific solutions not compromises. My experience has shown that the initial cost of the CERL Panel is about 50% more expensive to install than equivalent pneumatic systems. The new trend toward PLC's will result in a cost difference of 100% to 200% over a conventional pneumatic system. A shorter life expectancy and increased maintenance and training will make this Panel even less cost effective."

One expert had no additional comments.

Two experts had no input during the design phase. For one of these experts, the HVAC Control Panel was selected to test it for future HVAC projects. The Control Panel replaced a multizone control system.

One expert's "...biggest problem encountered in the design of the retrofit analog HW system which he was directly involved with, was the lack of accurate documentation on the existing system. The Design Instructions and Technical Specifications provided good guidance leading to a complete design package. The only problem, that I recall, with the standard guidance was that system interlock (HW system on/off relay and HW valve automatic shutoff E-to-P switch) hardware was not included in the control panel. The panel replaced a built-up pneumatic control system. No other option was considered."

To another expert, "Several problems exist in the design plans:

1. The technical specifications were never completed into a Guide Specification by detailed examination and wording. It is not clear in the Technical Specification that DDC is not allowed. The definition of `industrial grade components' is not clear, thus the specifications are open to interpretation.

2. The sequence for cascading control on heating/cooling systems allows for wasted energy by overlapping temperature ranges.

3. Air handling units are shown with cooling coils ahead of heating coils which would cause nuisance low limit alarm and possible freezing.

4. No sequence exists for supply fan/return fan matching of VAV system--a necessary design in some applications.

Consequently, design engineers believe that they `must' deviate from the Technical Specs to provide a fully workable system. The concept of standardization is lost."

AREA 4: INSTALLATION PHASE

During the installation phase, some areas of concern are the ease of installation (mounting and connecting to sensors, controlled devices and EMCS), calibration, training, and documentation. Please relate documentation to installation, calibration, and training where applicable.

Question 5

-What were your experiences with the Air Force Standard Panel during the installation of the entire HVAC system? (If this is not applicable to you, please feel free to consult co-workers who may have had more experience. If this is done, please record the individual's name, job title, and experience with the panel in a format similar to survey question 1. Remember the research is an effort to obtain as much information as possible and disseminate it to all the experts.)

ROUND ONE RESPONSES

One expert indicated the panel is easy to install since only a few wires are required for sensor connection. Training is required for the diagnostics and calibration. If CERL input is used from the Technical Specifications, calibration and operation are simple.

One expert was concerned with the additional cost of the panel. This expert found a higher first cost for electronic components, such as those in the panel, as opposed to pneumatic components in a built-up system. This expert estimates a 20-30% cost difference in components alone. This does not include diagnostic features and component housing costs.

One expert encountered no problems during installation and calibration after an explanation of the function of each component was given to the individuals calibrating the system. However, if explanations were not given, the panel has an intimidation factor which may inhibit proper installation and calibration.

One expert encountered no problems during panel installation.

One expert was not involved in panel installation and was not able to consult those involved in the telephone conversation time period.

One expert found "real smooth" installations.

One expert found the installation and calibration procedures too complicated for technicians to understand. This expert believes more training in electronic areas is required for these technicians.

One expert found incorrect installation procedures and calibration at a particular location. This system did not function properly due primarily to the installation of sensors which were incompatible with the panel controllers, improper design which allowed for a variation in component installation, components outside the panel being incorrectly connected and controllers calibrated with too narrow proportional band settings.

ROUND TWO RESPONSES

Two experts had no problems with installation and calibration.

One expert had the following comments:

"In general, the installation of the panels at the job site is not a complicated procedure. It only requires hanging the panel on a wall and terminating the field wiring and pneumatic tubing to the control panel. If the original step-by-step commissioning instructions are followed the whole installation phase is simplified.

The key to proper installation is proper planning and coordination before the panel is manufactured and sent to the job site. Any 'Shortcuts' in the design phase will create corresponding problems in the field. If the controls contractor 'educates' himself on what the standard panels should provide the Air Force in terms of simplified installation and maintenance prior to turning the project over to the Air Force, then the quality of training provided to the end user will be enhanced."

Another expert said, "The analog HW control panel installation and commissioning that I was directly involved with was straight forward. This can be attributed to the panel being factory tested and calibrated and the commissioning procedures were well documented."

One expert was not involved in the installation phase. The panel was installed by contract under an MCP project involving the B-1B bomber beddown.

To one expert, "The 'Standard Panel' does not set up clean with non-standard HVAC equipment and non-standard real life requirements going on in every building. Since the CERL Panel is only encountered with the military, contractors will be in a constant state of training and re-training as their people are moved within a company. People will have to be trained and on staff just to do government work. This additional training and staffing will be almost impossible to provide in remote areas."

AREA 5: OPERATIONS AND MAINTENANCE

Maintenance of the entire HVAC system, including the controls portion, is a major concern of the Air Force. Two important aspects of maintainability include (1) an ability to diagnose the HVAC system from the controls and (2) the reliability of the components of the control system themselves. Diagnostic capability includes the intimidation factor vs the panel's "seductiveness" to be used by the technician. Long-term reliability is difficult to assess since the panel has only been mandatory since July 1987, but please relay whatever information you have, including frequency of replacement and/or repair of components and frequency of calibration.

Question 6

-What were your experiences with the operations and maintenance of the Air Force Standard Panel? Please state, when making subjective statements, if the judgment is relative to pneumatic, electronic, DDC systems, or an ideal system which is yet to be developed or implemented. (If this is not applicable to you, please feel free to consult co-workers who may have had more experience. If this is done, please record the individual's name, job title, and experience with the panel in a format similar to survey question 1. Remember, the research is an effort to obtain as much information as possible and disseminate it to all the experts.)

ROUND ONE RESPONSES

Concerning maintenance, one expert indicated one panel had trouble with two E/P transducers and one reset module. However, no controllers required replacement. This expert also found 75-80% of the technicians were afraid to become familiar with the knobs and buttons composing the panel's diagnostic features. Once these features had been explained to them, the fear of touching the panel dissipated.

One expert believes many of the panel functions could be performed by EMCS. This expert also believes the panels are too complicated for many technicians and the Air Force training is not sufficient for the complication level as compared to pneumatic controls. The gauges are not used because the technicians don't understand their functions. Instead, technicians are used to tweaking components in an effort to solve a problem, not analyzing it using diagnostics. Training is difficult at base level, especially on bases which use the zone concept. Although the panels are too complicated, this expert believes standardization is a step in the right direction.

One expert cited a situation during which the panel was used to expose deficiencies in an HVAC system.

One expert believes the hidden costs in electronic components are due to the inability of the technicians to properly troubleshoot and calibrate electronic systems. This inability, coupled with the problems with electronic components due to heat generation, results in a shorter life for electronic components (12-15 years) compared to pneumatic components (20-22 years). This expert believes if technicians familiar with only pneumatic systems are expected to work with the electronic components in the panel without proper training, damaged or bypassed components will result. This expert believes the hybrid (electronic controllers and sensors with pneumatic actuators) system mandated by ETL 83-1, Change 1 is a step in the right direction, but more training is required and it may necessitate hiring technicians with a higher level of education. Additionally, this expert is not convinced the Air Force receives the hybrid system it asks for in every case.

One expert believes less maintenance trouble and customer complaints result from the panel than from built-up or separate component systems.

One expert found many problems with controllers in two different types of panels. Once the controllers were replaced, no further problems were experienced.

Two experts found no problems with their panels' operation to date.

ROUND TWO RESPONSES

Two experts had no problems with operations and maintenance. The experts found that the panels never need adjustment or calibration.

One expert does not have any changes to the above comments. He would like to add, however, that "Most bases do not have the level of personnel required to properly maintain these panels. Many bases can't currently handle EMCS maintenance, let alone the CERL panel. The Zone Maintenance concept will make the situation even more impossible."

For one expert, "The control system consists of a single zone system with a controller sensing return air to control the heating and cooling valves. The mixed air dampers are controlled by a comparator economizer which compares the outside air and return air. The system is fairly simple and practical.
We have had to replace the temperature controller, the

comparator and several indication meters even though the system had been in operation for only six months. This indicates a high failure rate for the electronic components."

One expert had the following comments:

"To achieve the full potential of the Standard Control Panels in terms of simplified operation and maintenance, a commitment must be made by the Air Force to enforce the specifications. Any shortcuts by contractors defeat the intent of a standard program.

1. Standard Design: Allows training of personnel for one application regardless of where they are stationed or transferred.

2. Standard Maintenance Instructions: Allows step-by-step troubleshooting of the system with both cause and effect explained for each step, i.e., what should be indicated by the diagnostics and what is causing the problem if improper indication is discovered.

3. Standard Diagnostics: Once a person has been trained on a single panel, the familiar diagnostics on future panels are no longer intimidating.

4. Standard Equipment: Allows maintenance personnel to be trained on generic electronic controls. There is no requirement for vendor specific training at each base as is required by DDC.

Each of these items has been documented in detail in the Design Instructions and Technical Specifications."

One expert said, "The analog HW control panel from one manufacturer (Manufacturer A) which he was directly involved with experienced repeated problems with the HW reset controller. This panel was eventually replaced with another manufacturer's HW control panel (Manufacturer B). This decision was made because, in a separate application, Manufacturer B's HQ control panel had been working very well without any problems for about 2 years.
Additionally, laboratory performance testing of standard analog panels 1, 3, 4, and 8 showed that each performed as expected with the exception only of one manufacturer's FSC static pressure control panel. This panel's soft start feature did not work properly."

AREA 6: FUTURE USE

Question 7

Considering all the pros and cons of your Air Force Standard Panel installation, would you install another one? Why or why not?

ROUND ONE RESPONSES

This question was not asked during the first round of the survey, hence, no responses are provided.

ROUND TWO RESPONSES

One expert said yes, he would install other panels. However, the Control Panels installed at this location do not have controls parts which are readily available. Therefore, a different brand would be requested.

One expert said, "Due to the time lag for their construction between mandating design and system acceptance, too few systems have been installed to determine overall effectiveness of the program, but we believe program and system to be sound. It would seem appropriate to evaluate and revise the Technical Specifications to get `bugs' out but maintain the program. Obviously, standardization implies a long term commitment."

Another expert said that the manual adjust set-up is great for the technicians to use in testing and calibrating the system. Overall, provided there was a debugging of the electronic components, they would like to have more panels installed due to the ease of maintenance.

One expert responded, "Yes. Only if required to by the spec."

One expert had no comments.

One expert-"I prefer the Standard Panel over DDC or pneumatics in government applications, but it is a bit outdated. The Army's new Single-Loop Digital Control (SLDC) Panel has been designed to overcome several of the drawbacks of the Analog Panel. I prefer the SLDC Panel over the Analog Panel."

AREA 7: ADDITIONAL COMMENTS

Please provide any additional comments you may have about either the Air Force Standard Control Panel or the Delphi technique employed to solicit and consolidate expert opinions. Include, if possible, other sources of potential experts in this area. These individuals may be included in the final (third) round of this survey or be provided as sources for future research in this area.

Thank you for your participation and sharing your opinions. Please mail this survey within ten days of receipt to AFIT/LSG (Bldg 641), Wright-Patterson AFB, OH 45433-6583. A stamped, pre-addressed envelope is enclosed for your convenience.

ROUND ONE RESPONSES

One expert mentioned work done by the US Navy using control systems composed of DDC boards. The primary problem with these systems was the inability of DDC controls to talk to each other due to the lack of a common language.

Four experts were not able to make further comments during the telephone conversation time period.

One expert mentioned the possible replacement of the single loop analog controllers with single loop microprocessors. This expert believes that, due to the advantage of microprocessors in space, i.e., only one panel required to house many controller functions, microprocessors are the wave of the future in Standard Panels.

One expert wishes the Air Force had more panels installed because the panels are so simple to maintain, have good control, and don't require the technicians to know so many systems.

One expert predicts a company will be able to make the panel very cheaply and underbid the "good" companies for business. When this happens, the Air Force will end up with junk. To avoid this, the expert suggests the Air Force write a super performance specification.

ROUND TWO RESPONSES

Four experts had no additional comments.

One expert said, "The SLDC Panel being developed by the Army is based on the same concepts, but has several advantages over the analog control panels. It is less expensive to apply because there is only one panel versus 8. Also, it provides more elements of standardization including

interchangeable controllers, ease of EMCS interface, a back panel which allows for standardized wiring and standard rail mounted devices.
The SLDCs are state-of-the-art digital controllers which are readily available and fully interchangeable not only between different control applications (PID, setpoint reset, dual input, and economizer), but can also be interchanged with a different manufacturer's controller because standard 4-20 mA I/O signals provide more features at less cost than the industrial grade analog controllers. Each SLDC can display it's [sic] own process whereby the maintenance person can manually modulate the end-device. These features eliminate the need for most of the diagnostic features (knobs, buttons, and displays) presently available with the analog panel. In addition, most SLDCs have a self-tune feature which greatly simplifies the commissioning procedure."

One expert said that one advantage in using the Standard Control Panel is the training of the base maintenance personnel in a select type of controls and control strategy.

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This study conducted research into the field of heating, ventilating, and air conditioning (HVAC) controls. Specifically, the research attempted to determine if the Air Force Standard Control Panel would aid in solving the Air Force's problems with complicated and unreliable HVAC controls.

The researcher conducted an experiment and a Delphi survey of experts. The experiment compared the Standard Panel with a pneumatic built-up system. The analysis included a comparative investigation of the installation, calibration, and operations of each system and a statistical analysis and comparison of the drift of each system's mixed air and supply air controllers. The Delphi survey included eight experts in the controls field who were familiar with the Air Force Standard Panel. The survey included seven questions and was conducted in three rounds.

No conclusions could be drawn from the statistical results of the experiment. However, the researcher concluded from the results of the qualitative portion of the experiment and the consensus of the Delphi experts that the Standard Panel was not superior to other controls systems in terms of design and installability (to include calibration) but was superior in terms of ability to maintain setpoint (to include overall operability) and diagnostics capability.

This research is valuable to the Civil Engineering (CE) community, the Air Force, and the controls industry as a whole because it attempted to include all aspects of all controls systems. Additionally, it performed a head-to-head comparison of two controls systems. If the conclusions reached by this research are applied, benefits to the Civil Engineers in terms of reliable and maintainable control systems, as well as to CE's customers in terms of a comfortable environment, will most certainly be realized.